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ON THE REFLECTION AND TRANSMISSION OF ELECTRIC WAVES BY SCREENS OF RESONATORS AND BY GRIDS.[1]

By F. C. Blake and C. R. Fountain.

1. Introduction.

EXPERIMENTS on electrical resonance for linear strips of metal have been conducted in a number of ways. Garbasso[2] worked with the reflection of electrical waves from wooden walls covered with linear resonators, parallel and uniformly distributed. He found that there was a selective absorption of the waves, getting high reflectivity when the resonators were in tune with the vibrator and then only. Garbasso and Aschkinass[3] measured the deviation of electrical waves through a prism built up of linear resonators on glass plates, the transmitted wave falling on a small parabolic mirror, itself constructed of resonators. They observed that the deviation depended upon the length of the resonators constituting the receiving mirror. Thus they found that both the refraction and the absorption decreased with increasing wave-length. Aschkinass and Schaefer[4] measured the transmission of electric waves through screens of resonators both when in air and when immersed in certain liquid dielectrics. In this way they obtained the refractive indices of the dielectrics for the wave employed.

[1] Read before the American Physical Society, Oct. 28, 1905.

[2] Garbasso, Atti Acc. di Torino, Vol. XXVIII., pp. 470 and 816, 1893. Journal de Physique, Vol. 22, p. 259, 1893.

[3] Garbasso and Aschkinass, Ann. der Physik, Vol. 53, p. 534, 1894.

[4] Aschkinass and Schaefer, Ann. der Physik, Vol. 5, p. 489, 1901.

The present experiments were undertaken at the suggestion of Professor E. F. Nichols with the view of studying more completely than hitherto the passage of electric waves through systems of linear resonators and, if possible, to throw further light on the question of the relation between the length of the wave and its corresponding resonator-length.

2. Apparatus and Wave-length.

Vibrator. — The vibrator was of the customary three-gap or Righi type placed in the focal line of a cylindrically parabolic mirror. It consisted of two brass balls (*BB*, Fig. 1), each 0.952 cm. in diameter, sparking in olive oil, the lead-in copper wires forming the air gaps *AA*. The two auxiliary spheres were two knobs of 0.15 cm. diameter fused on the ends of the lead-in wires. They were made small in order to disturb as little as possible the characteristic vibration of the two principal spheres. By means of sealing-wax the two balls *B*, *B*, were attached to glass tubes, through which the lead-in wires passed. To avoid line effects these wires were drawn through an opening in the mirror directly behind the vibrator and brought out as close together as non-sparking would allow. The air-gaps *A* and *A*, were usually about 0.4 cm. long. The whole was surrounded with a glass reservoir *G* for oil, provided with suitable inlet and outlet tubes (not shown) and fitted with rubber corks through which the glass tubes led. Back of the mirror these tubes were attached to a thumb-screw arrangement by means of which the length of the spark-gap *O* in oil could be altered at will. The efficiency of the vibrator was found to be a maximum when the balls were all but touching, *i. e.*, when the length of *O* was a very small fraction of a millimeter.

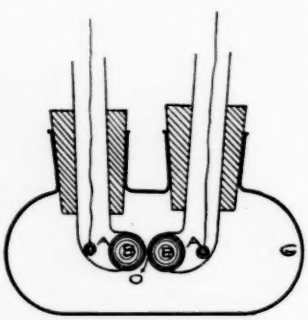

Fig. 1.

The source of energy was a 10-inch induction coil, with interrupter and condenser removed, connected to a 110-volt 60-cycle alternating-current circuit. In this way the use of an interrupter,

so frequently unsatisfactory, was avoided. The current in the primary was reduced to 7 amperes by suitable resistance in circuit.

Early in the work it was found that the oil surrounding the spark gap hindered the escape of the decomposition gases due to the spark. The axis of the vibrator was therefore changed from the vertical to a horizontal position and a constant stream of oil was led through the chamber *G*, entering below the spheres *BB*.

Receiver. — The wave detector was of the Klemenčič type, differing from the form used by Willard and Woodman[1] only in minor details. The diameter of the iron and constantan wires used was 0.0025 cm. These wires were soldered to copper strips 2 mm. wide fixed on wood and then they were crossed and joined to copper wires of larger size leading to the galvanometer. These larger wires were drawn away from the receiver immediately back of the thermal junction, so that no wire was exposed to the waves beyond the width of the copper strips. The total length of both the iron and constantan wires was thus not more than 3 mm. each. All junctions were soldered, as little solder as possible being used on the thermal junction itself so as not to lower too greatly its sensitiveness. This receiver was placed with its length horizontal in the focal line of a second parabolic mirror. The two mirrors were of sheet zinc and of equal aperture 70 cm. across by 63 cm. along the axis. The focal distance was 7.5 cm. A second, or check, receiver was placed directly in front of the sending mirror at a distance of 23 cm. from the vibrator and connected with a second galvanometer. This receiver will be spoken of as the check receiver, and the one in the receiving mirror as the main receiver. The resistance of each was about 2 ohms. As all junctions were soldered the resistance of neither receiver varied appreciably. The receiver resistances were always measured before and after a curve was taken. When, as happened occasionally, anomalous results were obtained in the midst of a curve, checking up the receiver resistances generally revealed an unsoldered or broken junction.

Galvanometers. — The galvanometers were of the du Bois-Rubens two coil type, triply ironclad. Owing to the proximity of all sorts of heavy street traffic and varying electric currents from tram and

[1] Willard and Woodman, PHYS. REV., Vol. 18, p. 3, 1904.

lighting circuits it was found necessary to hang the galvanometers from wall brackets by Julius suspensions and to add additional armor. For the latter purpose sheet iron was employed, five layers being wound spirally, separated from one another by strips of cork-rubber matting. In this way the magnetic disturbances were generally not more than five scale divisions for galvanometer C (attached to check receiver) and three for galvanometer M (main receiver). As the readings for the curves were generally large, some 200 or 300 scale divisions, the error due to these extraneous disturbances was small. The sensitiveness of M was 2.5×10^{-9} amperes, C 2.2×10^{-9} amperes. With coils connected in multiple the resistance of each galvanometer was about 2.5 ohms.

A rather elaborate system of mercury-cup connections was inserted as a key-board between the receivers and the galvanometers to admit of cross connections for reducing the effect of magnetic disturbances by allowing the two galvanometers to be read always in the same direction, and the insertion of suitable shunts to reduce the larger readings to scale limits. The two galvanometers were accurately adjusted to the same period, four seconds for a complete swing. Having once adjusted them to this period they remained so steady it became unnecessary to touch them throughout the course of the work. Readings were obtained by noting the zero position and the first throw. The drift of the zero point was usually slow and so small as to make the reading of return swings unnecessary.

Tuning of the Receivers. — For this purpose the two mirrors were placed facing each other in the usual way, their focal lines being horizontal, 1.3 meters above the floor and 2.4 meters apart. To prevent air currents affecting the thermal junctions the apertures of both mirrors were covered with thin card-board and each receiver was surrounded by a small paper box.

By a preliminary experiment the check receiver had been shortened to a length of 3.5 cm. and it was kept constant at this length during the shortening of the main receiver. The tuning of the latter is plotted as a curve in Fig. 2. Abscissas are total lengths of the receiver in centimeters; ordinates, the ratios M/C of the galvanometer deflections. It is to be noted that the curve gives multiple

tones of the receiver, minima at even, and maxima at odd multiples of the fundamental length. This is as it should be, for the current in the receiver is a maximum when there are loops of potential difference at its ends. So far as it was carried the curve agrees with curves 1 and 2 obtained by Willard and Woodman.[1] Their curves show the harmonics of the vibrator but not the multiple tones of the receiver, for they did not start with sufficient lengths to show these.

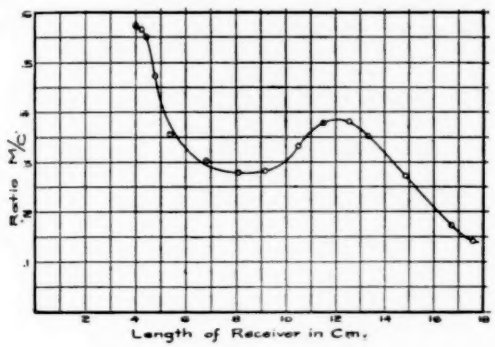

Fig. 2.

By trial it was found immaterial whether the check receiver was tuned — for some of the work it was kept at the length 3.5 cm.; later it was changed to the proper resonance length, 4.0 cm.

Deterioration of the Vibrator. — Although a check receiver was employed to take account of the irregular action of the vibrator, it was found that, starting with the vibrator in a new and fresh condition, the ratio M/C gradually lessened as the spark gap deteriorated. In addition to the constant eating away of the material of the spheres a filament of carbon from the decomposed oil would gradually bridge the gap, both causes tending to lessen the radiation. By making and breaking the circuit a few times this bridge could be torn away and the galvanometer readings immediately following its disappearance were invariably very large. Before this unsatisfactory condition of the vibrator was reached, however, it was generally renovated. To do this it had to be taken all apart, because the construction and the small size of the balls prevented the possibility of turning new portions of the spheres into position

[1] Willard and Woodman, l. c.

for sparking by merely rotating the glass tubes to which they were attached. In all cases the vibrator was not touched during the progress of any one set of readings although tests were made which showed that any measurement could be duplicated to within 5 per cent. after the vibrator had been removed, readjusted and replaced. The ordinary duplication for any curve-point, obtained by simply repeating readings was usually within 2 per cent.

The following sample series of figures illustrates the decrease in the ratio M/C as the condition of the vibrator grew poorer. Each figure is the mean of seven readings, successively taken under constant conditions; 0.804, 0.802, 0.798, 0.784, 0.790, 0.784, 0.776, 0.764, 0.777, 0.768, 0.754, 0.750, 0.741, 0.740, 0.732, giving a total variation of 9 per cent. Moreover, the series shows that the falling off is somewhat irregular. Now it was found that an increase in the length of the spark gap O invariably produced a decrease in the energy radiated and a corresponding decrease in the ratio M/C. In general, it would seem that the violent action to which the vibrator was subjected, together with the constant wearing away of the brass spheres gradually lengthened the gap; and yet at any one instant a projecting particle of brass might easily have shortened it for the moment, thus accounting for the irregularity in the decrease of the ratio.

But however irregular the vibrator's action, due to *any* cause, one would expect the ratio M/C to hold constant, provided both receivers wese sufficiently far removed from the vibrator as to be affected by *pure* radiation only. The observed decrease in this ratio indicates that the check receiver, distant from the vibrator 23 cm. or a little more than two wave-lengths, was close enough to receive some of the energy that periodically flowed back into the vibrator. Since these two portions (the *pure* and the *impure*) of the radiation which reaches the check receiver do not vary proportionally, for a small amount of energy emitted by the vibrator the denominator of the fraction would be relatively too large.

Instead of removing the check receiver to a greater distance it was easier to eliminate as far as possible all irregularity in the vibrator's action in the following way: Whatever varying system was being measured, readings of a second constant system were

alternately taken, giving a second ratio M'/C'. The quotient $\frac{M/C}{M'/C'}$ should not contain any effect of irregularity in the vibrator's action. For example, suppose one was measuring the transmission of energy through a system of resonators as their length was gradually shortened. He could take alternate readings of the transmission through air, obtaining a second ratio M'/C', and thus eliminate various irregularities.

Measurements of the Wave-length. — For measuring the length of the principal wave emitted by the vibrator the interferometer method[1] was employed. The separating surface was a grid of fine copper wire (B. & S., No. 34) mounted on a wooden frame 125 by 100 cm. The distance between the wires was 3 cm. The fixed mirror was zinc, 117 by 95 cm.; the movable mirror was a silvered

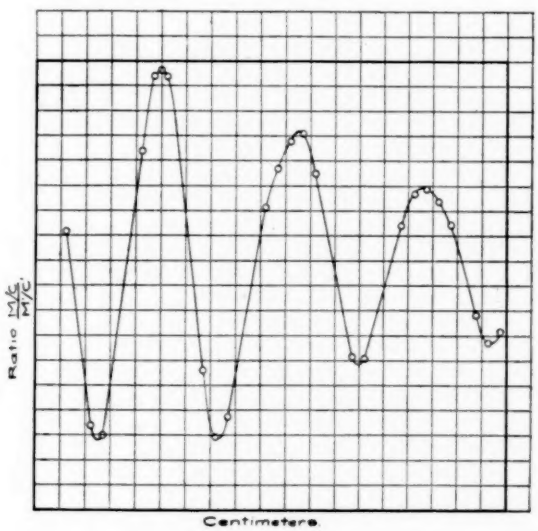

Fig. 3.

surface on the front face of a piece of plate glass 122 by 96.5 cm. This silver mirror was supported in one of two equal compartments of a sliding framework, itself encased in another framework arranged to move in the direction of the wave along a set of ways. The

[1] For the advantage of this method see G. F. Hull, PHYS. REV., Vol. 5, 1897, and Willard and Woodman, l. c.

sliding device, by allowing the removal of the silver mirror from the path of the wave, afforded alternate readings of the effect of reflection from a third metal mirror fixed in position back of the movable one. Thus the ratio M'/C' was obtained. The interference curve is shown in Fig. 3, the ordinates being the ratio $\frac{M/C}{M'/C'}$. The complex character of the radiation is shown by the unequal spacing of successive maxima and minima. For estimating the wave-length from this curve only the principal maximum and its two adjacent minima were considered, for it is in the immediate neighborhood of this maximum, where the two plane mirrors are equally distant from the separating surface, that the heads of the two wave-trains combine most strongly. In this way the wave-length came out 9.9 cm. An almost identical curve was obtained by using a separating surface with the wires 1.5 cm. apart. Had the spacing been 2.2 cm. the sharpest maxima and minima possible would have been obtained.

3. RESONATORS IN AIR.

The energy transmitted and reflected by various systems of resonators in a plane both in air and on glass was measured as their lengths were shortened and the results are plotted as curves in Figs. 6, 8, 9 and 10. All of the useful details as to the distribution of the resonators for the curves shown are collected into Table I. Tin-

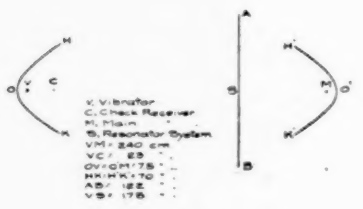

Fig. 4.

Fig. 5.

foil strips 2 mm. wide were employed throughout the work, their length being always parallel to the electric force of the wave, and in its plane for the transmission measurements. The arrangement of apparatus for transmission is shown in Fig. 4 and for reflection in Fig. 5; both diagrams are drawn to scale. The reflecting angle was 12° 45′, with a cosine of 1 approximately. To avoid diffuse

TABLE I.

Distributions of Resonators.

Designation of Curves.	Number of Columns.	Number of Resonators in a Column.	Distance between Columns (Adjacent Edges).		Distance between Resonators Sidewise (Axially).	Length of Resonators.		
			At Beginning.	For Resonance.		At Beginning.	For Resonance.	
Fig. 6, T and R.	7	39	1.0	5.7	3	10.0	5.3	
" 6, T_1.	13	20	0.7	1.1	6	5.3	4.9	Air.
" 6, T_2.	13	12	1.0	2.6	10	6.0	4.4	
" 6, T_3.	15	5	1.0	1.6	20	5.0	4.4	
" 8, T and R.	13	39	0.5	3.5	3	6.0	3.0	
" 8, T_1.	7	39	1.0	8.0	3	10.0	3.0	Sheet Glass.
" 8, T_2.	13	23	0.5	3.2	5	5.5	2.8	
" 9, T and R.	13	39	1.0	4.45	3	6.0	2.55	Plate Glass.
" 10, T and R.	7	117	0.5	6.0	1	10.5	5.0	
" 10, T_1.	7	75	1.0	7.0	1.5	10.0	4.0	Sheet Glass.
" 10, T_2 and R_2.	7	59	0.5	7.7	2	10.5	3.3	
" 10, T_3.	7	12	0.5	8.5	10	10.5	2.5	

reflection from the walls of the room the apparatus was arranged diagonally with respect to them.

By a carefully conducted series of tests with a grid of fine wires 5 mm. apart the wave emitted by the vibrator was found to be 100 per cent. plane-polarized. Accordingly it was deemed unnecessary to insert, after the method of Aschkinass and Schaefer,[1] such a grid in the path of the waves. Moreover, a screen to cut off diffraction effects was not used for it was thought that better comparative results for transmission and reflection would be obtained without its use, since in the one case such a screen could not be used. However, to make sure that the diffracted energy was small, a plane metal mirror the size of the resonator system was inserted at *S*, Fig. 4, and the galvanometers read. The effect at *M* was less than 1.5 per cent. of the incident energy. In Fig. 5 such a mirror was inserted in a position close to the vibrator mirror but so inclined as to reflect none of the energy into the receiving mirror. A small effect, 1.4 per cent., was still felt at *M*. In both of these cases the phase relation that this diffracted energy bore to the main portion of the energy was unknown and so it was not corrected for in any of the curves. It shows itself especially in curves *R*, Fig. 6, length 0 cm., and *R*, Fig. 12, distance 8 cm.

In the transmission work, to avoid the possibility of interference effects at the check receiver *C* the resonator system *S*, Fig. 4, was placed relatively close to the receiving mirror. By choosing a resonator system that reflected the larger proportion and yet transmitted some of the energy and by making careful tests as it was moved along the line *VM* (Fig. 4), no effects due to interference could be detected at *C*.

Fig. 5a.

The resonator system *S* was fitted into one of two equal compartments of a sliding framework (Fig. 5, *a*). For the work on transmission through resonators in air the other compartment was left empty; for resonators on glass it was either empty or fitted with a bare glass plate, the duplicate of the one supporting the resonators. For the work on reflection the second compartment

[1] Aschkinass and Schaefer, l. c.

held a plane metal mirror, the silver mirror used in measuring the wave-length serving as the check reflector. By sliding S back and forth across the path of the waves readings were alternated between the two compartments, giving the ratio $\frac{M/C}{M'/C'}$. Thus the reflection or transmission was measured.

As a rule only five readings constituted a set for any given length of strips, three of the resonator system under observation and two of the check system; for during the progress of the work it had been found that better results were obtained for a small than for a large number of readings, since in this way excessive deterioration of the vibrator was avoided.

Of the curves in Fig. 6 for resonators in air T was taken with the

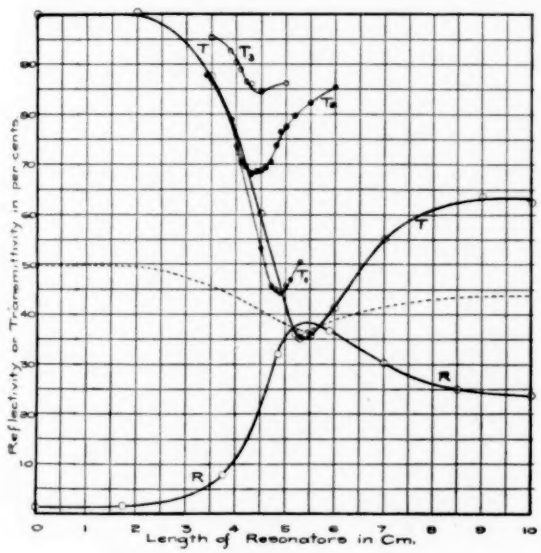

Fig. 6.

strips attached to cross section paper and R, T_1, T_2 and T_3 to tracing cloth. By a previous test both of these substances were found to have an index of refraction of 1 for the wave employed. R was the first one of the curves taken and shows that the resonance-length was passed unexpectedly. It was carefully located, however, at 5.3 cm. in the T curve. As the mean of T and R, the dotted curve shows

that the scattered radiation is a maximum at the resonating length. This agrees with expectation on the assumption that none of the energy suffers degradation. It is seen that when the strips are shorter than 2 cm. or $\frac{1}{5}\lambda$ there is practically no absorption.[1]

It was thought worth while to see what would be the maximum reflection obtainable from a set of resonators of the above length, 5.3 cm., using a more dense distribution. In the work with resonators on glass (to be mentioned later) it had been found that a change in the side-on distance between resonators altered the length for maximum resonance while a change in the end-on distribution, within the limits investigated at least, did not affect it. Accordingly, keeping the side-on distance the same as before, 3 cm., the number of columns was increased from 7 to 13, making the distance between adjacent edges of adjoining columns 0.7 cm. The coefficient of reflection of this set was 79.0 per cent.

Two other distributions of resonators in air were tried — T_1, obtained from the set just mentioned by removing alternate horizontal rows, and T_2. For T_1, with strips 6 cm. apart, resonance occurred at the length 4.9 cm.; for T_2, strips 10 cm. apart, at 4.4 cm.

To show the relation between side-on distance and resonating-length the curves in Fig. 6 are summarized in *A*, Fig. 7. It turns

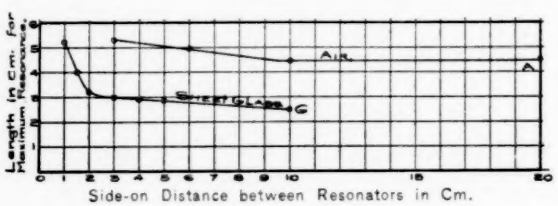

Fig. 7.

out a straight line making an appreciable angle with the axis of abscissas, and shows that the magnetic fields of the resonators do not cease to influence each other until the resonators are nearly a whole wave-length apart. That the resonance-length should decrease with increasing distance between the strips was to be expected; for since

[1] Following Aschkinass and Schaefer the word "absorption" will be used in this paper to mean the diminution in energy in passing through a resonator system; it thus includes reflection, scattering and degradation into heat if any.

at any instant the currents in the resonators are all in the same direction the effect of induction is reduced by decreasing the distance between them; hence in order to respond to a given wave the capacity of the resonators must be increased, that is, they must be lengthened.

4. Resonators on Glass.

The results obtained for resonators on glass are shown by curves in Figs. 8, 9 and 10. For the most part sheet glass 3 mm. thick was used. For the transmission work the check system for getting M'/C' was often a second plate of sheet glass bare of resonators, but as this was compared with air or empty frames the ordinates represent the actual percentages of reflection or transmission. The functions of the two glass plates were often interchanged. To facilitate the process of cutting down the resonators coördinate paper

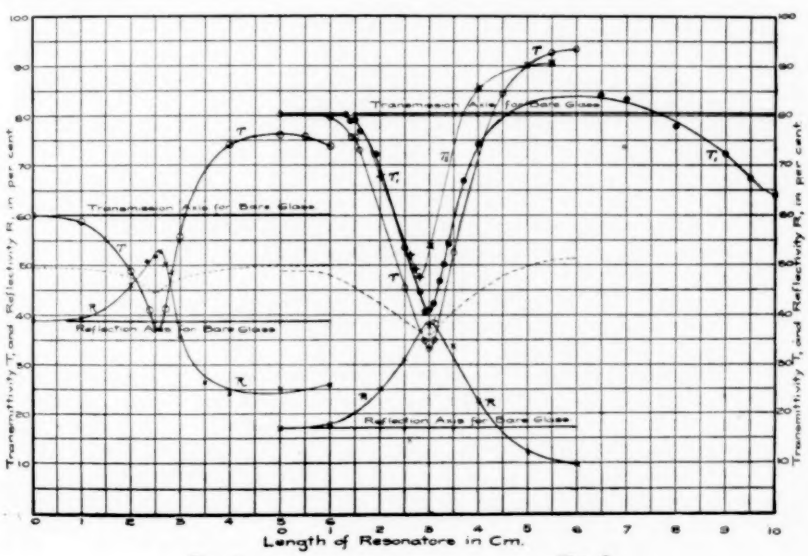
Transmission Axis for Bare Glass
Reflection Axis for Bare Glass
Transmission Axis for Bare Glass
Reflection Axis for Bare Glass
Length of Resonators in Cm.
Transmittivity T and Reflectivity R, in per cent.
Transmittivity T, and Reflectivity R, in per cent.

Fig. 9. Fig. 8.

was pasted on the backs of both plates, after the method of Aschkinass and Schaefer. When bare they agreed quite well with each other and with themselves from day to day, never deviating more than 2 per cent. of the incident energy from the mean, viz., 80 per cent. transmission and 17 per cent. reflection.

A study of curves T and T_1 in Fig. 8 in connection with the

table shows that within the limits there specified a change in the end-on distance between resonators does not affect the resonance-length, which was 3 cm. in both curves. An attempt was made in both of these curves to locate the first upper partial of the vibrator. Though weak it was detected, as shown for the length 1.5 cm. It was found impossible to locate any upper partials beyond the first for if present they were too feeble to admit of measurement.

Perhaps the most interesting feature of the curves in Fig. 8 is that they all cut the axes for bare glass. This means that for strips on glass 3 cm. apart and of length about twice the resonating length the system transmits more and reflects less energy than for the glass plate bare. We shall refer to this phenomenon as that of *extra transmission*. It will be discussed later. It is seen that it is a maximum in this case for a length twice the resonance-length; and as shown by T it is a rather large effect, being 13 per cent. for this 13-column distribution.

The dotted curve shows, as in Fig. 6, increased scattering at the resonance-length. This result was obtained in every case where the trouble was taken to secure both the T and corresponding R curves.

As is usual with sheet glass the pieces used were slightly warped and so to make sure that none of the effects obtained were due to lack of planeness, especially because of the finite dimensions ($12 \times 10\lambda$) of the glass, one set of curves was taken using plate glass (6 mm. thick). They are shown as curves in Fig. 9, and it is seen that the type is the same as before. The distribution was the same as for Fig. 8, T except that the end-on distance at the start was 1.0 cm. instead of 0.5 cm. The *extra transmission* is slightly greater than before, about 16 per cent. It is seen, too, that the reflection from the thicker glass is greater and the resonance-length less (2.55 cm. instead of 3 cm.) than for the sheet glass. For resonators this same distance of 3 cm. apart in air the resonating-length was 5.3 cm. It is doubtful if, following Aschkinass and Schaefer, the index of refraction of the glass could be obtained from these figures, for the thickness of the glass as well as the fact that it is on only one side of the resonators serves to make the relation a complicated one.

A comparative study of the curves in Figs. 8 and 10 with reference to the table of distributions shows that a variation in the side-on distance between strips materially alters the resonance-length and in a manner similar to the case of resonators in air.

The most typical resonance curve is T_1, Fig. 8, for which the strips were 3 cm. apart. When 5 cm. apart the effect is smaller, as shown in T_2, and for 4 cm. distance the curve (not shown) lies in value between T_2 and T.

For distances apart smaller than 3 cm. (see Fig. 10) the absorp-

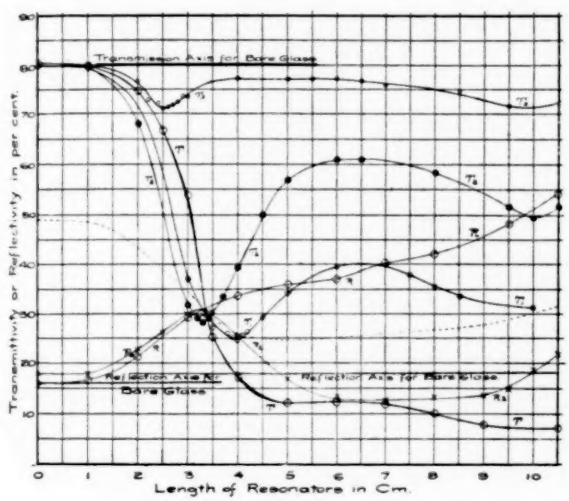
Transmission Axis for Bare Glass
Reflection Axis for Bare Glass
Transmittivity or Reflectivity in per cent.
Length of Resonators in Cm.

Fig. 10.

tion keeps increasing in amount with diminishing distance, but the sharpness of the resonance continually grows less until for a 1 cm. distance the exact location of the absorption maximum is indefinite, so flat has the curve (T) become. It was estimated at 5.2 cm., but it may easily be 2 or 3 mm. more or less than this. Thus we may say that for resonators on glass the absorption-maximum practically disappears when they are $\frac{1}{10}$ of a wave-length apart. The same thing seems probable for resonators in air.

The dotted curve in Fig. 10 is the mean of R and T and shows how great the scattering becomes when the resonators are close enough together to interfere strongly with one another. The mean

of R_2 and T_2 is not shown, but the fact that R_2 cuts the reflection axis for the bare glass plate while T_2 does not cut the transmission axis shows the magnitude of the scattered energy. For zero length R and R_2 differ by 2 per cent. of the incident energy, due to lack of planeness of the glass and to experimental error.

In all of the work on reflection the resonator face of the glass plate was toward the vibrator, but in the transmission work it was found immaterial which surface faced the vibrator. For instance, T_2, Fig. 8, was taken with the resonator surface of the glass toward the vibrator while T was taken with it in the opposite position. In fact, to test the idea, when the resonance length of T was reached the plate was purposely turned 180° ; there was no alteration in the transmitted energy.

As was found for the case of the main receiver (Fig. 2) one would expect for the resonators a second absorption-maximum at a length three times the fundamental length, and indeed this second maximum appears in its proper position in T_2, Fig. 10. But R_2 does not support T_2 in this respect and in T_1, Fig. 8, it is displaced 1 cm. to the right. The displacement of this second maximum is shown most strongly in T_3, Fig. 10, taken for a set of resonators 10 cm. apart. It would seem that for causes difficult to explain, the location of this second maximum for any given case cannot be successfully estimated ; to be able to predict it the law of scattering would need to be known. It is interesting to notice, however, that in all the curves, no matter what the length of maximum resonance, this second maximum occurs at the length 10 cm. It is difficult to give an unequivocal interpretation of this result, but it should be noted that at the beginning of any seven-column distribution curve the end-on distance between resonators was small (though in no case less than 5 mm.) and for such distances capacity effects due to charges on the ends of the strips might be felt. This is not borne out, however, by curve A Fig. 11 (see below), for if the charges on the ends of the strips exert an appreciable influence for end-on distances as small as 5 mm. the first point on this curve should not be on the straight line the curve shows.

Although the relation between the first and second absorption-maxima is not clear from the experiments, still the first absorption

minimum always (including the case of resonators in air) occurred at the length twice the fundamental length, provided the strips were not closer together than 2 cm. Now Rubens and Nichols,[1] working with heat-waves 24 μ long reflected from fluorite, measured the reflection from silver resonators on glass for a number of different lengths varying by successive steps of 6 μ and found maxima of reflection for the lengths 12 μ and 24 μ and a minimum at 18 μ. In other words, they obtained reflection maxima for resonators whose length was a whole number of half wave-lengths, whereas we find such maxima only for odd multiples of the half wave-length. The form and distribution of the resonators on glass studied by Rubens and Nichols were so different from any case examined in the present paper that no strict comparison between their results and the present ones is possible. One assumption used in the interpretation of their results, namely, that the resonators and the glass background reflect separately and independently, seems from the present results very doubtful.

Curve G in Fig. 7, summarized from Figs. 8 and 10, expresses the relation between the side-on distance between strips and the resonance length. It becomes a straight line for distances greater than 4 cm., and though it slopes less than A does, it still makes an

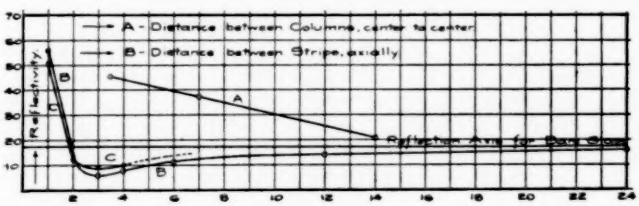

Fig. 11.

appreciable angle with the axis of abscissas. Had points on A been obtained for distances under 3 cm. the curve would show in all probability the relatively sharp bending that G does for such distances.

Starting with a dense distribution of columns of strips of the resonating-length it was thought interesting to measure the reflection as alternate columns were removed. Accordingly measure-

[1] Rubens and Nichols, PHYS. REV., Vol. V., p. 152, 1897.

ments were taken of a 27-column set of resonators 3 cm. long, 3 cm. apart sidewise and 0.5 cm. apart end-on, then for a 13-column set and finally for seven columns, care being taken, of course, always to leave the central column. Using as abscissas the distance between the axes of adjoining columns the curve (*A*, Fig. 11) plots a straight line.

5. Long Strips on Glass.

In the endeavor to get more light on the observed phenomenon of *extra transmission* strips 2 mm. wide and of a length equal to the entire width of the plate were pasted on the glass at intervals of 4 cm. Such a set reflected 8 per cent. and transmitted 92.9 per cent. by measurement, the bare glass reflecting 17.5 per cent. This set being then rendered worthless by further experimentation which did not prove fruitful, another set of long strips 1 cm. apart was prepared. The coefficient of reflection having been obtained alternate strips were then removed and measurements again taken. The fact that the greatest *extra transmission* for a system of double the resonating-length had been obtained when the strips were 3 cm. apart (*T*, Fig. 8) had led us to suspect that 3 cm. was a critical distance, and so for the first removal of strips only every third instead of every other one was left. The results are shown in curve *B*, Fig. 11, while curve *C* shows the corresponding figures, estimated from Figs. 8 and 10 for a system of double the fundamental length. Both the reflection for 1 cm. distance and the *extra transmission* for the other distances are slightly greater for *B* than for *C*. Now curves R_2 and T_2, Fig. 10, show that while for a 2 cm. distance there is less reflection from the system of double length than from the bare glass plate, still the extra energy is scattered, not transmitted; *T* and *R*, Fig. 8, on the other hand, show that when the distance is 3 cm. the excess is actually transmitted, that the scattering is nothing. Hence it would appear that *extra transmission* occurs for long strips on glass when further apart, say than 2.5 cm. or $\frac{1}{4}\lambda$. We are inclined to think that it occurs for strips on glass any distance apart greater than $\frac{1}{4}\lambda$ and of any length greater than the fundamental length provided the length chosen is not near a secondary absorption-maximum; this idea was only partially tested however.

Perhaps the simplest explanation of the observed phenomenon of *extra transmission* and correspondingly decreased reflection which may be at present tentatively offered, is that the combination of metal strips and glass constitute a medium with a refractive index different from that of glass alone. The optical dispersion formula [1]

$$n_\lambda^2 = b^2 + \sum \frac{M}{\lambda^2 - \lambda_1^2}$$

leads directly to such a result. Thus if for the glass alone $n = b$, then when the plate is covered with resonators of a given length,

$$n_\lambda^2 = b^2 + \frac{M}{\lambda^2 - \lambda_1^2}$$

in which n_λ is the index of refraction for the wave-length λ of the incident-radiation and λ_1 is the wave-length corresponding to the natural period of the resonators; b^2 is the dielectric constant of the medium. Hence when $\lambda_1 \gtrless \lambda$ then $n \lesseqgtr b$. In all cases where *extra transmission* was observed $\lambda_1 > \lambda$ hence $n < b$, which is as it should be to give decreased reflection and a correspondingly increased transmission.

Seen from this point of view, the present case is analogous to that of quartz in the visible spectrum, where $n < b$, hence quartz shows smaller reflection and larger transmission for visible than for the longer electric waves. In both instances the anomalous behavior is due to the presence in the medium of structures which respond to longer waves than those present in the incident radiationl

So far as the present writers are aware this phenomenon of *extra transmission* has not hitherto been noticed for electric waves.

6. Long Strips Cut into Resonating-lengths.

The resonating-length having been determined for certain side-on distances between strips both in air and on glass, it was considered of sufficient interest to compare the reflection percentages from long strips entire and when cut into resonating lengths. Strips 77.3 cm. long and 3 cm. apart in air reflected 39.8 per cent. of the incident energy; when these were cut into 13 columns of resonators 5.3 cm. long with a 0.7 cm. end-on distance the reflection was 79.0 per cent., a two-fold increase.

[1] Drude's Optics (English translation), p. 391.

For the same distance apart on glass *extra transmission* occurred in the case of long strips, and so where strips of great length when entire reflected only 5.6 per cent. of the incident energy, when cut into 27 columns 3 cm. long and 0.5 cm. apart end-on the reflection was 46.0 per cent., an eight-fold increase.

7. Reflection and Transmission of a Wire Grid.

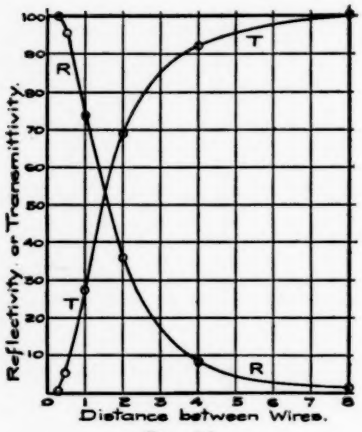

Fig. 12.

For measuring the reflection and transmission of a wire grid fine copper wire (B. & S. No. 34) was attached to a large (125 × 100 cm.) wooden frame at intervals of 2.5 mm., and measurements were taken as the grid-constant was successively increased by removing alternate wires. The results are shown as curves in Fig. 12. The reflection is seen to be total when the spacing is 2.5 mm. or one fortieth of a wave-length and zero when it is 8 centimeters or four fifths of a wave-length.

8. Comparison of Wave-length with Resonator-length and with Receiver-length.

Using two different separating surfaces the principal wave-length was found to be 9.9 cm. Although in getting the curve in Fig. 2 for the tuning of the receiver no means were provided for taking account of the deterioration of the vibrator the error thus introduced in locating the tuned length of the receiver at 4.0 cm. is of the second order. This is confirmed in the curve, moreover, by the second maximum occurring quite accurately at 12.0 cm. Thus the ratio of wave-length to receiver length is 2.47, confirming MacDonald's[1] value of 2.53 over Poincaré's[2] value of 2.

Curve *A*, Fig. 7, shows that neighboring resonators no longer influence each other in a way to change the length for maximum resonance when a whole wave-length apart sidewise. Beyond this

[1] MacDonald, "Electric Waves," p. 111.

[2] Poincaré, "Les Oscillations Electriques."

distance the curve becomes a straight line, and the length of maximum resonance in a system so spaced should be the same as that for a single uniform linear resonator. For 10 cm. waves the chief resonance-length was found to be 4.4 cm. and the ratio $\frac{\text{wave-length}}{\text{resonator-length}} = 2.25$, which agrees neither with Poincaré's nor with MacDonald's theoretical value, but is midway between the two values.

The experimental evidence for this result is given in curves[1] T_2 and T_3, Fig. 6. T_2 shows the transmission as a function of the resonator length when neighboring resonators were 10 cm. apart sidewise, and T_3 shows the same function for resonators 20 cm. apart. The abscissas of the minima in both cases are fairly well marked and cannot be read as low as 4 cm., which would be necessary to establish MacDonald's ratio, nor can they on the other hand, be read as high as the 5 cm. length, required by Poincaré. The only question which can arise therefore is one concerning the accuracy of the wave-length measurement. The writers feel reasonably sure that the wave-length cannot be in error by an amount large enough to bring about even an approximate agreement with either theory.

Willard and Woodman[2] found an agreement with MacDonald's ratio for the resonance length of thermoelectric receivers, and their result is confirmed earlier in the present paper. In the thermoelectric receivers, however, a relatively high resistance occurs at the thermojunction and also a sharp constricting of the current stream lines. Such conditions undoubtedly affect the linear dimensions for maximum resonance, and it is therefore not surprising to find the resonance length for receivers different from that for uniform linear resonators.

9. Conclusions.

As a result of the present study it appears:

1. That for a system of linear resonators, the length for maximum resonance is, within fairly wide limits, independent of the distance apart of resonators in the direction parallel to the electric force, but

[1] The observations for curves T_2, T_3 were made for the writers by Messrs. Woodman and Webb after the other experiments embodied in this paper were completed.

[2] Willard and Woodman, l. c.

varies in an inverse manner with the distance between resonators in a direction perpendicular to the electric force.

2. That the mutual influence between resonators at side-on distances greater than a wave-length of the incident radiation ceases to affect the length for maximum resonance appreciably.

3. That the resonator length for maximum resonance depends upon the dielectric properties of the plate to which the resonators are attached.

4. That secondary resonance maxima occur only at odd multiples of the fundamental resonating length.

5. That neither the Hertz-Poincaré nor the MacDonald ratio for the quotient of wave-length by resonator length holds for a uniform linear resonator.

6. That certain systems made up of resonators of lengths differing with the distribution over the surface of a glass plate, transmit more energy than the same glass plate when bare, and that a simple and general explanation of this result is afforded by the theory of optical dispersion.

7. That it is possible to increase the reflection from a grid of very long strips any distance apart by cutting them up into lengths equal to the resonance length for that distance.

8. That the distance apart of fine wires in a grid to be perfectly opaque to electric waves of length λ when the wires are parallel to the electric force, should be of the order $\frac{1}{40}\lambda$. When at a distance $\frac{4}{5}\lambda$ apart the same wires transmit practically all of the incident radiation.

In closing we wish to express our indebtedness to Messrs. L. E. Woodman, H. W. Webb, F. A. Thomas and S. R. Williams for their kindly assistance rendered at various times in taking some of the observations. To Professor Hallock we are grateful for kindly interest, encouragement and friendly advice. We are especially indebted to Professor E. F. Nichols, who suggested the problem and some details of the methods for solving it.

PHOENIX PHYSICAL LABORATORIES,
COLUMBIA UNIVERSITY,
February, 1906.

NOTE. — Since the foregoing paper was written the results of an investigation by M. Pietzold, Ann. d. Phys., 19, p. 116, 1906, in some respects similar to the present one, have come to the attention of the writers.

THE DURATION OF THE AFTERGLOW PRODUCED BY THE ELECTRODELESS RING DISCHARGE.

By C. C. Trowbridge.

Introduction.

THE phosphorescence which is produced in a gas by the electrodeless ring discharge and known as the afterglow, has been studied chiefly by J. J. Thomson,[1] H. F. Newall,[2] and J. B. B. Burke,[3] who have established a number of facts concerning the phenomenon. The nature of the afterglow, however, has not been explained and the conditions on which it depends have been little understood.

The purpose of the investigation described in the present paper was to determine some of the conditions under which the afterglow is formed by making a series of systematic observations on the duration of the afterglow in air at different pressures and with different conditions of the electrical system.

The duration of the afterglow does not appear to have been systematically studied heretofore and a number of new facts have been determined by this method of investigating the nature of the phenomenon.

The subject is of interest, both on account of its theoretical bearing, and because the afterglow has a suggestive resemblance to certain unexplained glows which occur in the upper regions of the earth's atmosphere, namely, the persistent luminous streaks or trains which are produced by very large meteors. It was in connection with an investigation relating to these meteor trains that a study of the afterglow was made.

The observations on duration of the afterglow have been extended also to very low temperatures, such as might be expected at great

[1] Thomson, Recent Researches, p. 185, 1893.
[2] Newall, Proc. Camb. Phil. Soc., Vol. 9, p. 295, 1897.
[3] Burke, Phil. Mag., 6 s., Vol. 1, p. 342, 1901.

altitudes above the surface of the earth, by subjecting the rarefied gas in which the afterglow was formed to the temperature of liquefied air, and the behavior of the afterglow has been studied when under these conditions. This paper contains the following sections:

1. Previous investigations on the afterglow.
2. Arrangement of the apparatus.
3. Method of observation.
4. The variation of the duration of the afterglow with change of gas pressure.
5. The change in the duration curves when the electrical intensity of the field in the discharge vessel is varied.
6. Critical gas pressures where the afterglow is not readily formed.
7. The effect on the duration curve of changing the frequency of oscillation of the system.
8. The duration and behavior of the afterglow at liquid air temperatures.
9. Conditions which effect a change in the rate of decay of the afterglow.
10. The spectrum of the afterglow.
11. Points of resemblance between persistent meteor trains and the afterglow.
12. Summary and conclusions.

1. Previous Investigations on the Afterglow.

Worrem [1] and Sarasin [2] have given accounts of phosphoresence in rarefied gases produced by electrical discharges and both have agreed that it does not occur in the case of a pure simple gas.

The afterglow formed by the electrodeless ring discharge was first investigated by J. J. Thomson,[3] who found that the gases which show the afterglow are those which also readily form polymeric modifications, and that in the case of oxygen the glow seems to come from ozone and the phosphorescence to be due to the gradual reconversion of the ozone into oxygen.

In a paper on "Luminosity Attending the Compression of Certain Rarefied Gases," H. F. Newall [4] states that he obtained afterglows

[1] Worrem, Pogg. Am., Vol. 126, p. 643.
[2] Sarasin, Pogg. Am., Vol. 140, p. 425, 1870.
[3] Thomson, l. c. Conduct. of Electricity through Gases, p. 498, 1903.
[4] Newall, l. c.

of the following colors: silver-gray, yellow, green, old gold, ruddy yellow, and brilliant blue, and that he was led to connect white phosphorescence with mixtures containing oxygen and carbon compounds, and yellow phosphorescence with mixtures containing oxygen and nitrogen, and blue phosphorescence with mixtures containing oxygen and sulphur.

Newall found the spectrum of the afterglow to be continuous. He also observed the interesting phenomenon that when the gas in the apparatus was compressed in the ordinary process of pumping, a glow appeared. This glow was obtained only in the pump bulb and after an electrical discharge had taken place in the receptacle used for that purpose, which was connected to the pump bulb by a small bore tube six or eight feet long. The pressures at which he obtained the pressure glows were between 0.5 and 0.3 mm.

J. J. B. Burke[1] has also published a paper "On the Phosphorescent Glow in Gases." He found that when wire gauzes were placed at points along a tube through which the afterglow was diffusing, and these gauzes attached to the terminals of a small Wimherst machine in action, the afterglow appeared "to travel down the tube with undiminished intensity and velocity," and that when an electromotive force from 180 storage cells was substituted for that from the Wimherst, the result was the same. This is evidence that the glow does not accompany recombination of the ions. He showed that a destructive effect was produced on the afterglow by subjecting it to cathode rays, and also found "that the glow conducts as it passes through the gas." This subject was investigated at some length by Burke, but the above results seem to be the most important.

A paper by Percival Lewis[2] on a new phosphorescence phenomenon contains an account of an afterglow in many respects similar to that formed by the electrodeless discharge, especially in regard to its spectrum, to which reference will be made later on.

2. Arrangement of the Apparatus.

The method of producing the electrodeless discharge in the writer's experiments was the same as that originally adopted by J. J. Thomson.

[1] Burke, l. c.

[2] Lewis, Astrophys. Jour., XII., July, 1900.

The inner coatings of two or more Leyden jars, *LL*, Fig. 1, were connected to the spark gap *S* and also to the terminals of a powerful induction coil; the outer coatings of the jars were joined to the helical coil *C* which surrounded the glass vessel in which the discharge was produced. The vessel was connected to a mercury air pump provided with a drying bulb and a McLeod gauge.

The spark gap consisted of two brass balls one centimeter in radius each and their distance apart could be varied by means of a micrometer screw. Whenever a spark passed between the brass balls of the spark gap *S* the rapid alternating current set up in the coil *C* around the glass vessel *V* by the discharge of the jars gave rise to an alternating electromotive force in the gas in the vessel. At low gas pressures the ring discharge appears, which is followed under certain conditions by the afterglow.

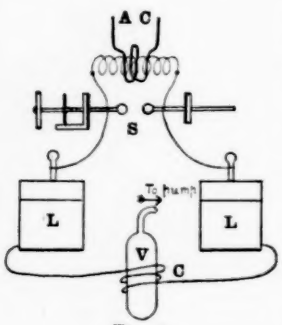

Fig. 1.

The theory of the electrodeless discharge has been worked out by Davis,[1] who used in the course of his experiments both the helical and spiral form of coil, and the only difference between the results obtained was that the discharge is somewhat more easily produced when the helical coil is employed, owing to the static discharge, perpendicular to the plane of the true ring discharge, due to the impedance of the helical coil.

When a large induction coil is employed it is very difficult to keep the balls at the spark gap bright, and therefore it was found best to allow them to become clouded by the discharge in order to assure constant conditions for successive discharges.

It was at first attempted to make the observations by using an induction coil with direct current and a Wehnelt interrupter, but owing to the variations in the action of the interrupter this arrangement was not employed. An unusually powerful induction coil was then procured, and operated by a 60-cycle alternating current. This method proved satisfactory.

The vessel employed at first was a single glass bulb, as shown by

[1] B. Davis, PHYS. REV., XX., March 3, 1905.

V in Fig. 1, which was surrounded by a coil of wire connected with the Leyden jars, but it was necessary to discard this form of vessel because the phosphorescence of the glass produced by the discharge was so bright and persistent as to prevent the moment when invisibility of the afterglow occurred from being noted. In one experiment, after the electrodeless discharge had ceased, the phosphorescence of the glass was observed to remain for *twelve minutes*, air at atmospheric pressure having been let into the vessel immediately after the discharge.

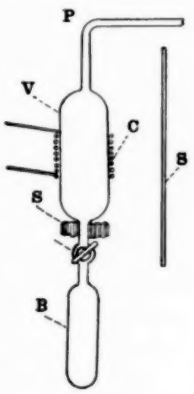

Fig. 2.

The vessel shown in Fig. 2 was finally employed, in which P is a tube of about 0.6 cm. bore leading to the pump, etc., V a glass vessel 7 cm. in diameter, B a small bulb into which the afterglow diffused, C a coil of eight turns of insulated copper wire, SS screens for cutting off the light from V when observing the afterglow in B, SC, stop-cock, 0.7 cm. bore.

3. Method of Observation.

The method of making the observations of the duration of the glow is explained in detail, because it is generally considered difficult to determine the moment of disappearance of a fading light with accuracy. As seen, however, from the curves in this paper, the various points showing the duration of the afterglow and the corresponding pressure lie within the curves in almost every case.

The duration of the afterglow was taken as the time between the instant of the cessation of the electrodeless discharge and that when the afterglow became invisible; the time being registered by a stop-watch reading to one fifth second.

In order to have constant sensitiveness of the eyes the observations were all made at night and the eyes were always carefully covered by a screen during the time when the electrodeless discharge was taking place. The readings were afterwards recorded by the aid of a dim light. The room and the apparatus were painted black which prevented reflections.

In Table I., four determinations of duration at different pressures

of the air are given. These show the agreement of successive readings of the duration of the afterglow in one series of observations. In all the curves given the agreement of the observations is nearly as good. Occasionally apparently abnormal conditions of the gas in the tube were encountered which interfered with the measurements. This matter is considered in the next section (4).

From the figures in Table I. it is evident that the errors from physiological sources are small. This is chiefly owing to the fact that the afterglow is too faint to produce after-images, and that the rates of decrease of intensity of the afterglow in the experiments made were quite rapid except at very low pressures, and thus the moment when invisibility occurred was readily noted at most pressures. The statement concerning the agreement of the readings does not apply, however, to the duration at certain "critical pressures," which are referred to especially in section (6).

At very low gas pressures the variation of the different readings in the same set were larger than at high pressures (as shown by the last column, Table I.), owing to the fact that the rate of decay of the intensity of the glow is slower as the pressure diminishes and the exact moment of invisibility is noted with difficulty.

TABLE I.

Readings of the duration at different pressure (from Series 12).

p = .28 mm. Duration in Seconds.	p = .125 mm. Duration in Seconds.	p = .107 mm. Duration in Seconds.	p = .020 mm. Duration in Seconds.
15.8	24.4	29.2	21.6
14.2	25.4	28.6	22.4
14.0	24.2	31.0	23.2
15.0	26.8	28.4	20.2
14.6	25.4	30.4	18.8
14.2	27.2	30.2	25.2
15.2	27.8	31.8	25.4
16.0	27.4	32.4	20.0
15.4	25.0	30.4	24.0
15.8	25.8	30.4	21.0
15.2	25.9	30.28	22.2

Average variation from the mean at 0.28 mm. pressure 0.62 sec. or 4 per cent.
" " " " " " 0.15 " " 1.08 " " 4 "
" " " " " " 0.107 " " 0.94 " " 3.1 "
" " " " " " 0.20 " " 1.86 " " 8.3 "

A series of observations consisted in determining the duration of the afterglow at from ten to fifteen different pressures, beginning at the pressure where the glow was first observed and gradually reducing the pressure by strokes of the pump until a pressure was reached where no afterglow could be obtained, or until it was too faint to be observed accurately. Usually, each determination was the mean of ten readings about one minute apart, and an entire series required from two to three and one half hours About four or five minutes was allowed to elapse each time the pressure of the gas was changed.

4. Variation of the Duration With Change of Gas Pressure.

Agreement of Curves Formed Under the Same Conditions. — It has been shown in a general way that the duration of the afterglow varied with the pressure, but no measurements have been published. My first attempts to make a continuous curve showing the variation of the duration with change of pressure were unsuccessful, because the first measurements covering a complete curve were not

Table II.

Spark gap 3 min. See Fig. 3.

Series 1.		Series 2.	
Pressure in Millimeters.	Duration in Seconds.	Pressure in Millimeters.	Duration in Seconds.
1.90	2.4	—	—
1.11	3.4	—	—
0.80	3.9	0.72	6.08
0.577	5.04	0.53	5.20
0.410	5.96	0.37	4.68
0.30[1]	3.7	0.27[1]	3.38
0.224	9.58	0.22	10.5
0.16	22.2	0.20	13.2
0.117	29.4	0.155	28.3
0.083	32.8	0.112	40.5
0.059	31.38	0.08	42.2
0.042	27.76	0.056	38.3
0.030	19.2	0.040	36.8
0.02	10.6	0.029	27.2
0.011	5.8	0.020	14.6

(Tabulated observations are omitted in all other series, but the results are shown by carefully plotted curves.)

[1] For consideration of durations at these two pressures see section 6.

made in one run, and it was later found that the duration of the afterglow changed if the gas remained in the discharge vessel for several hours even at the same pressure. It has been found that a continuous curve cannot be formed if fresh gas is admitted between observations, but if an uninterrupted run from high to low pressure is made a smooth curve is obtained.

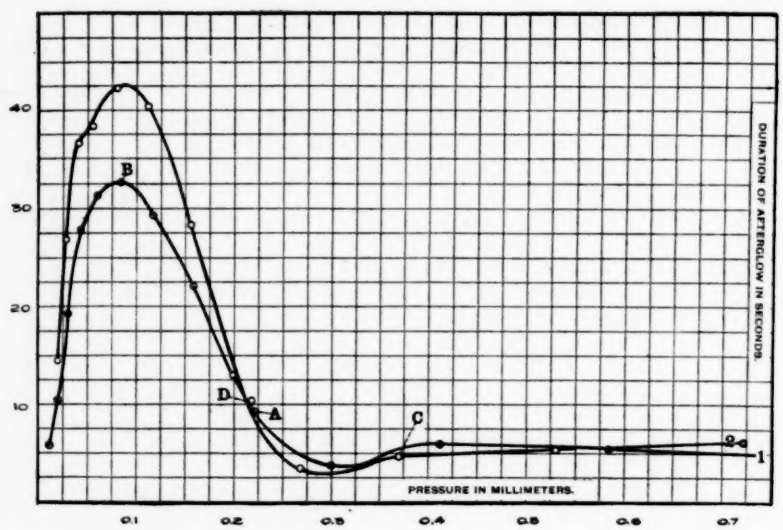

Fig. 3.

Series 1. Spark gap, 3 mm. Volts per cm., 45. Capacity, 6 jars. Period: 9.78×10^{-7} sec. Afterglow diffused to lower bulb at A, to drying bulb, etc., at B. Duration at .3 mm., mean of 10 observations, not counting a number of cases where no afterglow appeared.

Series 2. Same electrical conditions as Series 1. Diffusion to lower bulb first noticed at C, bright as afterglow in upper bulb at D, at .27 mm., mean of 24 observations, 3.4 sec. Seven other discharges caused no afterglow.

Series 1 and 2, in Table II., and Fig. 3, were made with the same conditions but several days apart, the difference of duration observed being due to the different states of the gas in the discharge vessel when the experiments were performed. The maximum and minimum points of the curve and the characteristic points of inflection are almost identical, which is the result of keeping the electrical conditions constant. Two other curves are shown in Fig. 7 which were made with a greater sparking potential than series 1

and 2 and hence a higher number of volts per centimeter acting on the gas. These curves were made with the same electrical arrangement and are similar but differ slightly in duration.

In regard to the general form of the curve, the duration in series 1 and 2, Fig. 3, is seen to gradually increase to .4 or .5 mm. pressure, then to decrease to a critical pressure where the afterglow is not always formed, then rise rapidly to a maximum at approximately .8 mm. and then fell to zero. In Fig. 4 three curves are

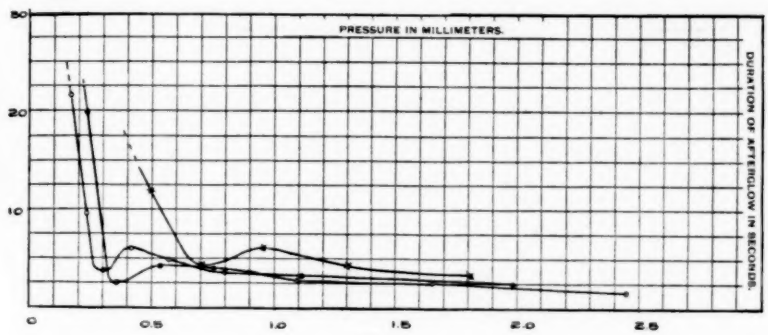

Fig. 4.

Curves showing the relation of the duration of the afterglow to the pressure at pressures greater than 0.5 mm.

given showing the duration of afterglows formed above .5 mm., the highest pressure at which the afterglow was obtained by me was 2.4 mm.

The Effect on these Curves Produced by Changes in the Gas. — In section 9 the causes bringing about the change of the rate of decay are considered. The changes are such that they unquestionably affect the duration curves. In one experiment it was found that the duration was lengthened 300 per cent. by ten successive discharges, and in others in one hour the duration increased 100 per cent. with no discharges passing during the period. However, in all the observations shown in this paper by curves the successive readings at one pressure were nearly constant as shown in Table I. The effect of an increase of the duration due to a gradual change of the gas in time could not have been more than 10 per cent. Such an effect would tend to displace the curve upward as the pressure is reduced. Moreover, the general shape of the curve, the points of inflection

and the effect of changes of electrical conditions are clearly defined in the curves and are but little affected by changes arising from the causes referred to above.

5. The Change in the Duration Curves when the Electrical Intensity of the Field in the Discharge Vessel is Varied.

If the spark gap in parallel with the capacity is lengthened an increased electrical intensity acting on the gas in the discharge vessel results. The intensity which can be obtained is largely limited by the surface insulation of the apparatus used. This is shown by a curve in Fig. 5 giving the relation of the spark-gap to the electrical intensity acting on the gas in the discharge vessel. A variation from 45 to 85 volts per cm. was obtainable giving a good

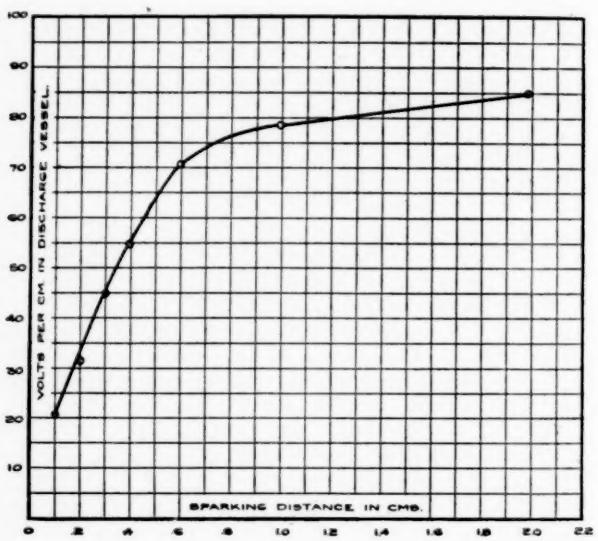

Fig. 5.

afterglow, and a series of observations giving the change of duration with pressure were made through the range as seen in Figs. 6, 7 and 8. Faint afterglows were also obtained at as low as 20 volts per cm. The electrical intensity was measured by means of a coil of wire temporarily replacing the discharge vessel and a micrometer

spark-gap in series with this test coil, as shown in Fig. 9 on page 294. The sparking potential was taken from Paschen's tables.[1]

The voltages are slightly greater than those measured owing to a potential perpendicular to the axis of the helical coil; the values in volts per cm., strictly considered, are only relative.

It is seen that the duration curve with 45 volts per cm., series 3, Fig. 6, has a sharp maximum and also a definite minimum. At the latter point the formation of the glow is uncertain. On increasing to 55 volts per cm., series 4, the maximum has begun to disappear and when the volts per cm. are above 70, series 5, 6, 7 and 8, Figs.

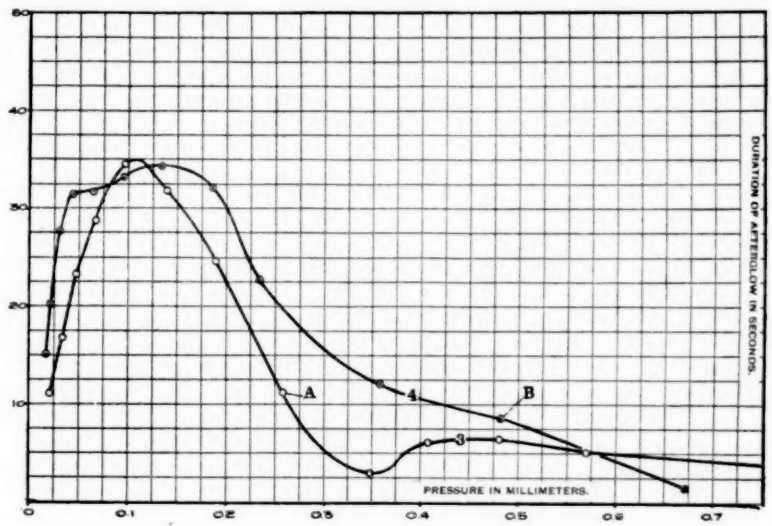

Fig. 6.

CURVES SHOWING THE EFFECT OF CHANGING ELECTRICAL INTENSITY.

Series 3. Spark gap, 3 mm. Volts per cm., 45; larger induction coil than used in Series 1 and 2. Capacity, 2 jars. Period: 5.65×10^{-7} sec. Afterglow first readily diffused to lower bulb at A.

Series 4. Spark gap, 4 mm. Volts per cm., 55. Other conditions as in Series 3. First diffusson to lower bulb at B.

7 and 8, the shape of the curve is seen to be completely changed. Therefore, when using high electrical intensities the maximum no longer occurs at pressures which give the greatest intensity but is shifted to the side of lower pressures, since the rate of decay of the afterglow is progressively lessened with diminishing gas pressures.

[1] Wied. Ann., 37, 1889.

This effect is partly concealed in the duration curves which do not show the relative initial intensities of the afterglow at different pressures. It is hoped that experiments now in progress on the rate of decay of the afterglow at different gas pressures may make it possible to show this quantitatively.

6. CRITICAL GAS PRESSURES WHERE THE AFTERGLOW IS NOT READILY FORMED.

In the ordinary process of forming a curve showing the change of duration with the change of pressure, a critical pressure was usually encountered where the afterglow was not always formed. In different experiments this pressure varied from .29 mm to .75 mm. according to the spark gap used. For all pressures in both directions from the critical pressure, except under certain apparently abnormal conditions, the duration of the afterglow was approximately constant for successive discharges, and followed every discharge when the afterglow once appeared.

Several typical cases will serve as illustrations: In series 1, Fig. 3, the duration of the afterglow was of 2.4 seconds at 1.9 mm. pressure. It then increased steadily to 5.8 seconds at a pressure of 0.4 mm. At the next stroke of the pump, bringing the pressure to 0.3 mm., the critical point was encountered. Here the mean of ten observations gave only 3.7 seconds duration, not including a number of discharges which produced no afterglow. In series 2 an afterglow of 6.1 seconds duration decreased steadily until at .27 mm. the mean of 24 observations was only 3.4 seconds, 7 discharges in this run giving no afterglow. The mean of the five longest durations was 5.5 sec. The critical pressure is seen by the curve, Fig. 3, to be approximately .29 mm.

In series 3, Fig. 6, the influence of the critical pressure was found at both .349 mm. and .259 mm. At both pressures there were about the same number of discharges where the afterglow was not formed. The critical pressure from the curve appears to be .35 mm., a different capacity being used in series 3 than in 1 and 2. It has been further observed that this critical pressure is the point at which the white discharge begins. In one set of 39 observations 23 discharges colored white mixed with pink were followed by an after-

glow, 3 pink with a little white gave no afterglow, and 13 pink produced no afterglow. Thus the formation of the afterglow at the critical pressure is intimately associated with the beginning of the white discharge. This is a curious fact, since in all the above series the afterglow had already occurred regularly at higher pressure after pink discharges.

It was only at low electrical intensities that the critical pressure was easily studied; with high intensities the afterglow rarely ap-

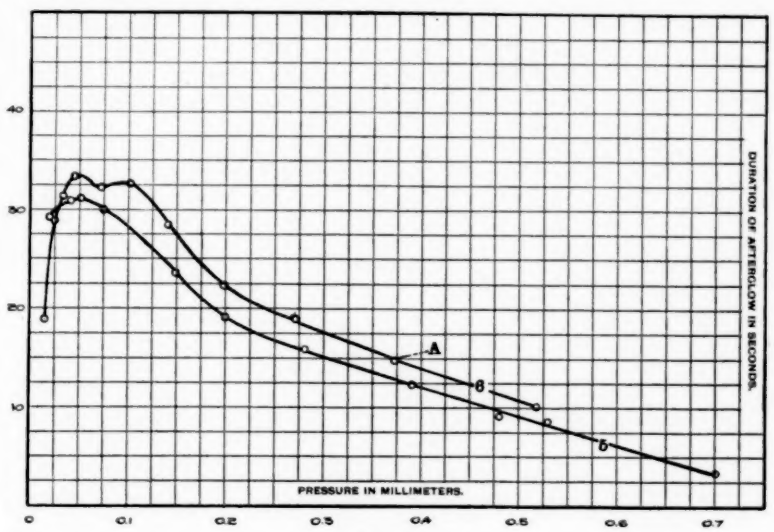

Fig. 7.

CURVES SHOWING THE EFFECT OF CHANGING ELECTRICAL INTENSITY.

Series 5. Spark gap, 6 mm. Volts per cm., 70.8. Other conditions as in Series 3.
Series 6. Spark gap, 6 mm. Volts per cm., 70.8 (duplication of series 5). First observation of afterglow from lower bulb at A.

peared until the gas pressure was reduced to a point at which the white discharge occurred.

The experiments thus seem to show that a critical point in the formation of the afterglow coincides with the pressure at which the white discharge begins, and also that the point moves toward higher pressures as the volts per cm. increase, as shown by Table III. In every case in this table except two, the afterglow had already appeared before the critical pressure was reached, and the duration at the critical pressure was less than previously obtained at higher pressure.

The variation in the critical pressure above 60 volts per cm. shows that the uncertain point extends over a greater range of pressure as the spark gap is increased. This may be due in part to the uncertain action of the spark gap.

TABLE III.

Intensity V. per cm. (Approx.).	Duration of Afterglow, Seconds.	Critical Pressure mm.[1]	Remarks.
45	3.7	0.30	10 observations; other discharges producing no afterglow not considered in mean.
45	3.4	0.27	24 observations and 7 misses critical pressure as shown by curve, .29 mm.
45	3.0	0.36-0.26	Curve shows critical pressure at 0.35 mm.
55	12	0.36	10 observations, 3 misses.
55	2.7	0.34	Missed repeatedly.
58	—	0.46	Only a few afterglows obtained.
71	5.0	0.54	Only a few afterglows.
71	3	0.87	
71	3.4	0.70	Many misses.
71	—	0.75	" "
78	4.1	0.75	4 misses to 1 afterglow.
80	4.1	0.69	Very irregular, no misses, probably below critical pressure.

[1] Approximate only, being the nearest gas pressure readings to the critical points on the curves.

7. THE EFFECT ON THE DURATION CURVE OF CHANGING THE FREQUENCY OF OSCILLATION OF THE SYSTEM.

The effect on the formation of the afterglow produced by employing different capacities in the system was determined, and it was found that the entire duration curve was slightly shifted by changing the capacity. The effect is due to the change in the frequency of oscillations, since the periodic time, T is equal to $2\pi\sqrt{LC}$, in which C is the capacity and L the self-induction of the system.

At the suggestion of Dr. Bergen Davis the same Leyden jars were used as were employed by him in his experiments on the electrodeless discharge, in order to determine if the maximum of the duration curve occurred at the same pressure as the minimum sparking potential, and if its position changed when the frequency of oscillation was varied. It was necessary to employ not only the same capacities, but also a coil having the same self-induction as in

his experiments in order to obtain the same frequency ; therefore the two inductances were carefully balanced on a double-wire Wheatstone bridge. The capacities employed were as follows :

Two jars, arranged as in Fig. 1, $C_1 = 1.6 \times 10^{-18}$.

Four jars, two in parallel, two in series, $C_2 = 3.2 \times 10^{-18}$.

Six jars, three in parallel, two in series, $C_3 = 4.8 \times 10^{-18}$.

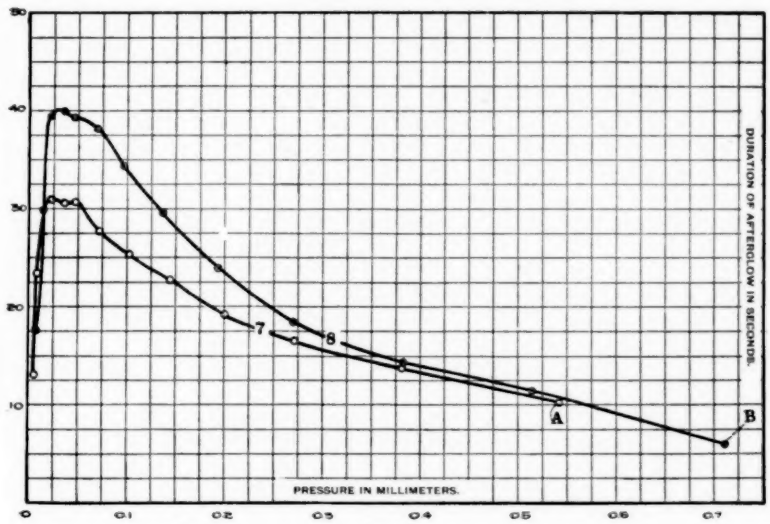

Fig. 8.

CURVES SHOWING THE EFFECT OF CHANGING ELECTRICAL INTENSITY.

Series 7. Spark gap, 10 mm. Volts per cm., 78.6. Other conditions as in Series 3. First observation of afterglow from lower bulb at A.

Series 8. Spark gap, 20 mm. Volts per cm., 84.8. First observation of afterglow from lower bulb at B.

The frequency of oscillations was changed without altering the ratio of the intensity acting on the gas to the potential at the spark gap, by making the above changes in capacity. The periodic time calculated from the formula $T = 2\pi\sqrt{LC}$, in which $L = 5.064$ cm. was as follows :

2 jars, $T_1 = 5.65 \times 10^{-7}$ sec. 4 jars, $T_2 = 7.87 \times 10^{-7}$ sec.

6 jars, $T_3 = 9.78 \times 10^{-7}$ sec.

It was not only found that the duration curve was shifted by changing the frequency of oscillation, but that the pressure giving the maximum duration of the afterglow when using low electrical inten-

sities corresponded to the pressure at which the electrodeless discharge is most easily started, or where the minimum sparking potential for air occurs as determined by Dr. Davis.

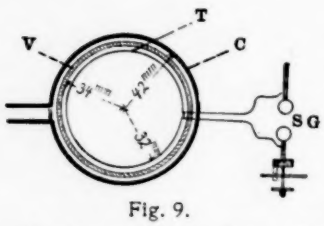

Fig. 9.

V, glass vessel; C, large coil; T, small test coil; S G, micrometer spark gap. Electrical intensity measured 2 mm. from inside of glass vessel.

It is only in the case of the afterglow produced by low electrical intensities that the coincidences occur, since it is only at such intensities, less than 50 volts per cm., that the gas pressure for maximum of luminosity of the afterglow more nearly corresponds to the pressure for maximum of duration.

The following table shows the gas pressures of the minimum sparking potential and the maximum of duration with the various frequencies used.

TABLE IV.

Capacity.	Periodic Time Seconds.	Minimum Sparking Potential Pressure.	Maximum of Duration of Afterglow Pressure.
2 jars	$T_1 = 5.65 \times 10^{-7}$	.070 mm.	.08 mm.
4 jars	$T_2 = 7.87 \times 10^{-}$	——	.091
6 jars	$T_3 = 9.78 \times 10^{-7}$	.096	.10

The exact pressure at which the sparking potential is a minimum is somewhat difficult to measure, but, considering the nature of the curves shown by dotted lines in Fig. 10, the agreement is fairly good.

According to Dr. Davis' experiments[1] the pressure at which the minimum sparking potential occurs for a certain period of oscillation (T_1) is .07 mm. for carbondioxide, .20 mm. for hydrogen and .25 mm. for helium, therefore it is probable that with similar electrical conditions the afterglows if they occur in the case of all these gases would have a maximum of duration at these pressures. The afterglow was found to occur in the case of helium by Davis.

The determination of the maximum of duration of the afterglow appears to be a simple and apparently accurate method of determining the pressure of the gas at which the discharge is most easily

[1] Davis, l. c.

started, and when this pressure is found the spark gap can be readily varied and the minimum sparking potential of the gas determined.

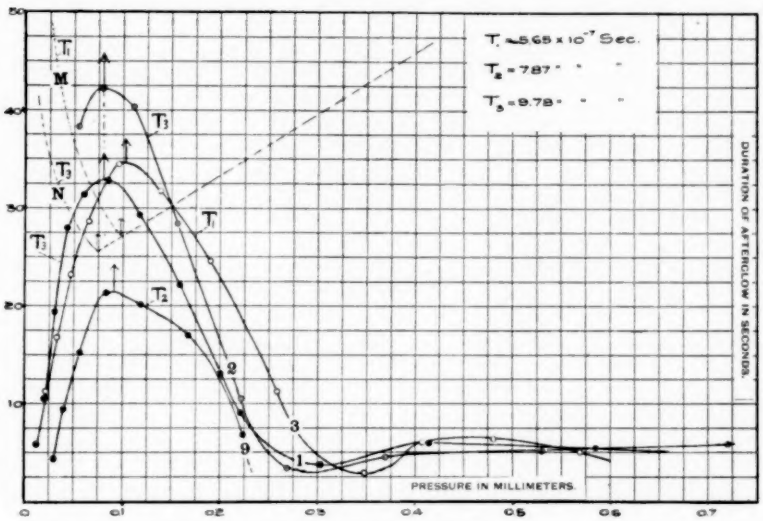

Fig. 10.

Series 1. Spark gap, 3 mm. (45 volts per cm.). Capacity, 6 jars. Periodic time, (T_3) 9.78×10^{-7} sec. Induction coil with A.C.

Series 2. Spark gap, 3 mm. Capacity, 6 jars. Periodic time, (T_3) 9.78×10.

Series 3. Spark gap, 3 mm. Capacity, 2 jars. Periodic time, (T_1) 5.65×10^{-7} sec. Larger induction coil than used in Series 1 and 2.

Series 9. Spark gap, 3 mm. 4 jars. Periodic time, (T_2) 7.87×10^{-7} sec. Same induction coil as Series 1 and 2.

Curves N and M, minimum sparking potential curves for air with T_3 and T_1 period of oscillations respectively. (Davis.) The vertical coördinate was intensity, the minimum value being 21.6 volts per cm. for N and 20.4 for M.

8. The Duration and Behavior of the Afterglow at Liquid Air Temperatures.

The afterglow was formed at liquid air temperatures in the following manner: The discharge vessel with the surrounding coil was placed within a cylindrical Dewar bulb, as shown in Fig. 11, and an attempt was made to form a duration curve of the afterglow when the vessel had remained for a considerable time immersed in liquid air. The afterglow was obtained at only a few pressures, as shown in Table V., and was then faint and short of duration. With

approximately the same conditions a comparison curve at 20° C. was made, which is shown by series 11, Fig. 13. The frost on the Dewar vessel and phosphorescence of the glass made the observations difficult.

TABLE V.

Pressure in mm.	Duration (at — 186° C.) in seconds.	Pressure in mm.	Duration (at — 186° C.) in seconds.
0.64	0	0.119	8.5
0.43	0	0.083	21.7
0.28	Slight glow	0.041	Slight glow
0.19	Slightly stronger glow		

The afterglow, therefore, appeared to be difficult to form at liquid air temperatures, which may be a direct result of a less powerful electrodeless discharge under these conditions. The apparatus was changed to the form as shown by Fig. 12, to determine if the afterglow when formed at normal temperatures would remain bright when it had diffused into a vessel cooled by liquid air. The protecting case about the Dewar vessel was designed to prevent frost from forming and obscuring the glow.

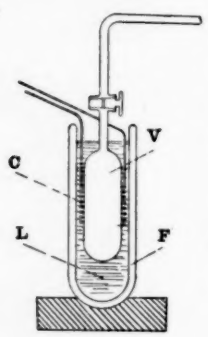

Fig. 11.

V, discharge vessel; C, coil, F, Dewar bulb, L, liquid air.

Two curves were made with as near as possible identical conditions. The first, series 12, Fig. 13, was at normal temperatures. The second, series 13, when the glow appeared in a vessel which had been cooled to approximately — 186° C. The observations were not begun until the McLeod gauge indicated the reduction of temperature in the cooled vessel was complete. The vessel was kept surrounded by liquid air for two hours.

The important facts revealed are that the afterglow appears bright and of long duration at — 186° C. when it is formed at a normal temperature and allowed to diffuse into the cold vessel; that the resultant curve is displaced considerably to higher pressure, in the present case from .08 mm. to .14 mm. pressure, and also that at every pressure from that corresponding to the maximum of

duration to lowest pressure, the afterglow at — 186° C. was much brighter than that in the discharge vessel, although of shorter duration. A comparison at each pressure of the duration of series 12 and 13 is scarcely possible, owing to the fact that the state of the gas was probably different in the two observations. Both series 12 and 13 were formed when the stop-cock connecting the upper and lower vessels (Fig. 12) was open. This permitted the afterglow to continually diffuse into the lower vessel. A series was later obtained in which the large stop-cock shown in Fig. 12 was closed after the discharge as soon as the afterglow had diffused into the lower vessel. A certain body of glowing gas was thus cut off at the temperature of liquid air. The curve obtained, series 14, is seen to be totally different from that of series 13 or when the stop-cock remained open, showing that when the glowing air is confined in liquid air the duration is much shorter than at normal temperatures. The afterglow also becomes less intense than that in the discharge vessel, therefore the shorter duration produced by the low temperature immediately on the closing of the stop-cock does not mean a more rapid discharge of energy.

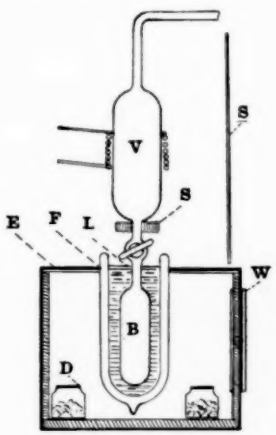

Fig. 12.

V, discharge vessel; B, small bulb; S S, screens, E, enclosure; W, glass window, D, drying material; F, Dewar bulb; L, liquid air.

The afterglow in the discharge vessel during the observations in series 14 increased from about 35 seconds to a maximum of several minutes (series 16). The exact curve was not obtained but a similar curve at about 20° C., shown by series 15 in Fig. 14, was made with the same electrical conditions.

A curious fact of these experiments was that when the afterglow surrounded by liquid air had disappeared, the stop-cock was opened a second time for a moment and then closed, the afterglow diffused into the bulb the second time lasted fully twice as long as when it diffused immediately after the discharge took place. Therefore the duration at — 186° C. in series 14, depended on how soon it was cut

off from the discharge vessel. The gradual rising of the duration to a maximum, as shown by series 14, Fig. 14, was probably partly affected by the increase of the rapidity of the diffusion as the pressure was reduced.

The most important fact that is shown by these last experiments (series 14), is that the afterglow can occur in the rarefied gas entirely isolated and surrounded by liquid air.

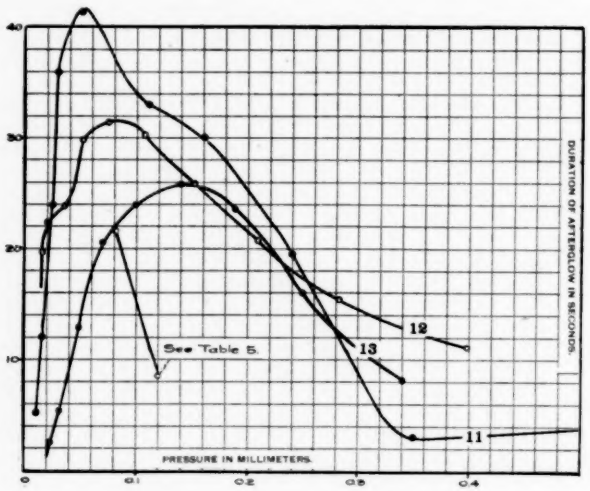

Fig. 13.

Series 11. Formed at 20° C. to show comparison with few observations of afterglow obtained at —186° C. See Table V.

Series 12. Formed at 20° C. for comparison with Series 13. 6 mm. spark gap, 6 jars.

Series 13. In bulb surrounded by liquid air, stop-cock open. Spark gap, 6 mm, 6 jars. Below .1 mm. pressure, afterglow brighter than glow in discharge vessel.

9. Conditions which Effect a Change in the Rate of Decay of the Afterglow.

The rate of decay of the intensity of the afterglow has not been measured but the duration of the phosphorescence has been observed to become lengthened under the following conditions:

1. *By Repeated Discharges in the Gas.* — The duration of the afterglow is increased under certain conditions by frequent sparking but the increase is noted chiefly when the gas is freshly admitted to the pump and when a number of discharges are passed through

it. Curves have been drawn showing a regular increase of duration from 20 seconds to several minutes. After a number of discharges the duration usually becomes constant.

2. *By Reducing the Pressure of the Gas.* — It has been demonstrated by experiment that increase of pressure of the gas after the afterglow is formed causes a shortening of the duration and a corresponding brightening of the afterglow, and that a reduction of pressure produces a lengthening of duration of the afterglow. This discharge of energy in the gas in the form of a glow by increasing

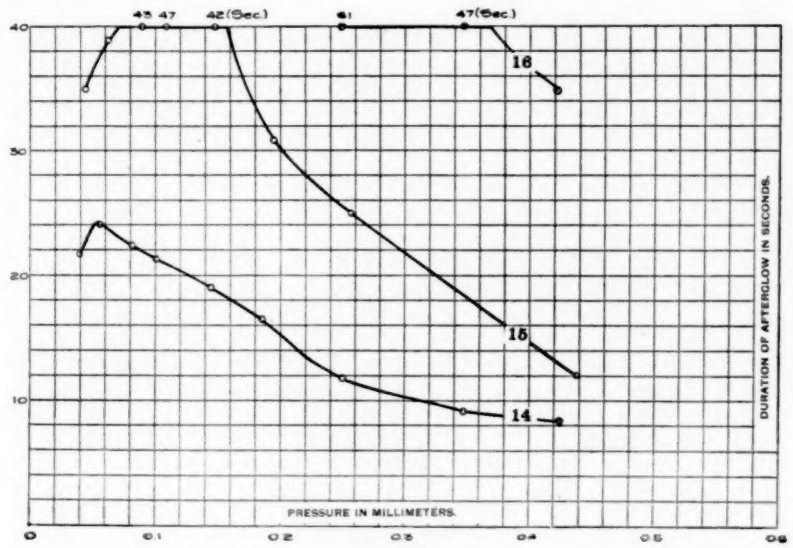

Fig. 14.

Series 14. Formed in the same manner as Series 13, except stop-cock closed after about one second. Bulb surrounded by liquid air. Spark gap, 6 mm. Capacity not determined, 2 large jars.

Series 15. Afterglow in discharge vessel formed at 20° C. for comparison with Series 14.

Series 16. The afterglow in discharge vessel corresponding to readings of afterglow of Series 15. Durations were too long to take entire curve.

the pressure seems to be similar to the pressure glows obtained by Newall, but in his experiments the pressure glows were only obtained in the pump bulb.

3. *By Permitting the Gas to Remain for Some Time in the Discharge Vessel.* — If the gas remains in the discharge vessel and

pump the duration becomes gradually longer. The initial intensity of the afterglow apparently remains the same. This diminution in the rate of decay of intensity occurs whether the air is isolated in a small vessel or connected with the pump and drying tubes. In one case after three weeks the glow increased from 45 seconds to 14½ minutes. The stop-cock leading to the pump was then closed and after three months an afterglow in the same air could be obtained which remained dimly visible for 19 minutes.

4. *By the Reduction of the Water Vapor in the Gas by Drying Materials.* — It has not yet been possible to determine to what extent the pressure of water vapor affects the duration of the afterglow, but it has been found that if the air laden with moisture is admitted to the pump the afterglows then obtained appear more reddish yellow and of short duration, so it is permissible to include water vapor as a fourth condition affecting the rate of decay of the glow. The amount of moisture present is rapidly reduced by the drying material present; but the change of rate of decay of intensity of the glow then depends on at least three conditions and it is difficult to determine to what extent each contributes to this change. The increase in the intensity of a red band in the spectrum of the afterglow occurs when water vapor is allowed to pass into the gas.

10. The Spectrum of the Afterglow.

The visual spectrum of the afterglow was observed carefully with a direct vision spectroscope having a scale electrically illuminated, and is given here more as a statement of the general character of the spectrum than the results of a precise spectroscopic study. Such an investigation will require a photographic method. The observations show the visual spectrum to be composed of four prominent and several faint narrow bands, two of which seem to have a line structure, as follows:

6200 — 6160; (approx.) band (see below).

* 5770 — 5730; band, more intense in the middle.

* 5460 ± 5; has the appearance of a clearly cut line. This line also occurs in the electrodeless discharge.

* 5400 — 5350, not as bright as 5460.

5100 — 5050; (approx.) very faint band.

* 4345 ± 5; very narrow band or a line; coincident with a corresponding line in the electrodeless discharge.

The bands and lines usually disappear in the following order; (1) (5100 — 5050), (2) (6200 — 6160), (3) (4345), (4) (5770 — 5730, 5460, 5400 — 5350), those starred being the most prominent at first.

The red band (6200–6160) is due to the presence of water vapor. After leaving the air in the apparatus for several weeks with drying material this band entirely disappeared, but on letting water vapor into the pump, etc., the band became nearly as bright as any of the other lines or bands, and when present decayed rapidly as shown above. The nearest correspondence to the red band is the diffuse maxima at 6170 of the oxygen spectrum.[1]

Two lines of the afterglow spectrum bear a close correspondence to two of the mercury spectrum. These lines are 5460 and 4348,[1] and are accounted for by the mercury vapor from the pump. The spectra of the Cooper-Hewitt lamp and the mercury glow in an incandescent lamp bulb both give bright lines which appear to be nearly coincident with those in the afterglow, namely, 5460 and 4340. The spectrum of the afterglow therefore seems to be a line spectrum of mercury combined with a band spectrum.

A yellow afterglow in nitrogen, formed in an *electrode* discharge tube, observed by Percival Lewis[2] showed a band spectrum. The wave-lengths of the centers of the bands were as follows: 6240, 5780, 5740, 5410. These bands show a close correspondence to those in the spectrum of the afterglow formed by the electrodeless discharge.

These observations do not agree with those of Newall,[3] who in a careful and long-continued spectroscopic investigation found the spectrum of the afterglow to be continuous, and only corroborates in part the statement of J. J. Thomson,[4] who records the spectrum in oxygen as continuous, and in air a faint continuous spectrum with a few bright lines. Davis[5] has observed three bright lines as the

[1] Atlas of emission spectra, Hagenbeck and Konen.

[2] Lewis, l. c.

[3] Newall, l. c.

[4] J. J. Thomson, Phil. Mag., 32, p. 335, 1891.

[5] Davis, l. c.

spectrum of the afterglow in helium excited by the electrodeless discharge. Newall observed the continuous spectrum a very short time after the discharge by means of apparatus which automatically cut off the discharge and exposed the afterglow. He states, however, that the spectrum of the pressure glows observed by him and described in section 1, was composed of four bands. In the writer's observations the spectrum was observed from a half second to a half minute after the discharge, and no change in its character appeared during that time. It seems evident that the spectrum of the afterglow in oxygen is continuous and that in air composed of a number of bright lines and bands, possibly combined with a faint continuous spectrum. Under certain conditions the lines 5460 and 4345 of the afterglow became exceedingly faint as compared to the rest of the spectrum, therefore considerable variation must be expected in the relative intensities of the lines and bands with different experimental conditions.

11. Points of Resemblance Between Persistent Meteor Trains and the Afterglow.

In the first part of this paper reference is made to the phenomena known as persistent meteor trains, and to the fact that a study of the afterglow was undertaken partly in order to ascertain if there were any points in common between these trains and the afterglow.

Meteor trains are masses of meteoric smoke left in the track of meteors and are self-luminous, sometimes glowing for over thirty minutes. The luminosity appears to be electrical in origin. The height at which the trains occur is between 50 and 65 miles from the surface of the earth. The afterglow bears a strong resemblence to them in a number of respects, and while no conclusion can be reached at this stage of the investigation, enough facts have been found to stimulate further inquiry. Only a short reference to the subject of meteor trains is possible here and a very brief summary of some of the points of resemblance between the two phenomena is as follows:

1. The motion of the meteor through the atmosphere produces an exceedingly high temperature and may bring about chemical or physical changes in the composition of the atmosphere in the track

of the meteor which on reverting to its original state gives out a phosphorescent glow, or the surrounding air may be highly ionized by the vaporizing meteor so that electrical discharges take place great enough to produce an afterglow like that following the electrodeless discharge.

2. The meteor train as well as the afterglow appears to be produced between definite gas pressures; in the former case the atmospheric pressures corresponding to the altitudes 50 and 65 miles, in the latter the air pressure in the discharge tube between 0.5 and 0.05 mm.

3. The rate of diffusion of the afterglow at certain pressures is of the same order as the outward diffusion of the glowing particles of the meteor train, or at the rate of several hundred feet per minute.

4. The spectrum of both appear to be composed of a few lines or narrow bands, but no observations of sufficient accuracy have been made on the spectra of meteor trains to make a more direct comparison possible.

5. Under certain conditions the afterglow dies out first where it is formed, and observations have shown that many meteor trains fade first in the center, or directly in the meteor's track where the train originates.

6. Absence of moisture seems to accompany long duration in the case of the afterglow, and at great altitudes the air must be very dry; thus if the meteor train is an afterglow the long duration of the phosphorescence may be partly accounted for by the absence of moisture.

7. The afterglow can occur in air cooled to $-186°$ C. The glow from the meteor train proceeds from a mixture of gas and extremely fine meteoric dust at the very low night temperature which exists at 50 or 60 miles above the earth's surface. Recently as low as $-79.5°$C. has been registered at approximately nine miles altitude by a baloon liberated at St. Louis by Rotch.[1] The observation was made at night in January.

A number of the above facts concerning meteor trains have been determined by the writer in a systematic study of the observations of this phenomenon made by different astronomers since 1860. A paper devoted to the subject will appear elsewhere.

[1] A. L. Rotch, Proc. Am. Acad. Arts and Sci., December, 1905, p. 350.

12. SUMMARY AND CONCLUSIONS.

A summary of the facts shown by the present experiments on the duration of the afterglow is as follows:

1. The visible duration of the afterglow can be measured with considerable precision if the eyes of the observer have been previously protected from the strong light so as to insure constant sensitiveness of the retina, and provided the fading of the afterglow is not too slow. Under these conditions errors from physiological causes affecting the measurements are negligible.

2. The electrical system remaining the same, similar duration curves showing the change of duration with change of pressure can be formed giving the same characteristic points of inflection, maxima and minima, but variations in duration in similar curves may occur owing to changes which take place in the gas.

3. The afterglows thus far observed appear over a range from 2.4 mm. to .002 mm. pressure. The range of the glows obtained by Newall being from about 0.6 mm. to .01 mm. only, and the glows observed by Burke being between 0.7 mm. and .02 mm.

4. The maximum of intensity of the afterglow and the maximum of duration are nearly coincident only at low electrical intensities. If the volts per cm. acting on the gas are increased above a certain value the afterglow is formed over a much greater range of pressures, and then the maximum of the duration curve no longer occurs at pressures which give the greatest intensity of luminosity but is shifted to the side of lower pressure, since the rate of decay of the glow is progressively lessened with diminishing gas pressures.

5. There is a critical point on the duration curve where the afterglow is only occasionally formed, and when obtained varies greatly in duration and intensity. This point corresponds closely with the pressure at which the white discharge begins. At this pressure, if the discharge is pink there is no afterglow; if pink intermixed with white then a glow of short duration occurs. The brightest and longest glows appear to follow the whitest discharges. At pressures on both sides of this critical point the time of duration of the glows are nearly constant for successive discharges and glows are obtained after every discharge.

6. The position of the maximum of the curve giving the change

of duration with change of pressure varies with the frequency of oscillation of the discharge, a greater frequency moving the maximum of duration towards higher pressure. With low electrical intensities the pressure giving the maximum duration of the afterglow always corresponds to the pressure where the electrodeless discharge is most easily started, which also varies with the frequency of the oscillation.

7. (*a*) When the electrodeless discharge is made to take place at the temperature of liquid air, the intensity and duration of the afterglow are both greatly diminished, although the glow is formed through a short range of pressures even at this low temperature.

(*b*) When the afterglow formed at 20° C. is made to diffuse into a bulb reduced to liquid air temperature, a passageway being left open to the discharge vessel, the curve of duration is similar to that at 20° C. but the maximum is very much displaced to a higher pressure. The glow is much brighter at pressures below the maximum of duration than it is at normal temperatures but decays more rapidly.

(*c*) If the passageway is closed as soon as the afterglow from a discharge has first diffused into the bulb cooled to liquid air temperatures, the glow is less intense and much shorter in duration than it is at 20° C. formed from the same discharge. Under certain conditions, however, which are not now understood, somewhat similar results are obtained at normal temperatures.

8. The rate of decay of the intensity of the afterglow may be gradually lessened by one or more of the following conditions: (1) A succession of discharges (in certain cases only), (2) change of the gas with time, (3) diminution of pressure while the gas is glowing, (4) gradual reduction of the quantity of water vapor in the gas (independent of 2).

9. While the rate of decay of the afterglow becomes less as the pressure of the gas is reduced, and the rate of recombination of the ions decreases with diminishing pressure at very low pressures, as shown by Hendren,[1] the glow is nevertheless not due to the recombination of the ions, unless fresh ionization occurs after the cessation of the electrodeless discharge, because in the case of small

[1] PHYSICAL REVIEW, Vol. XVI., November, 1905.

glass vessels the ions are known to disappear in a fraction of a second at pressures as low as those used in the present experiments.

10. The rapid drift of the glow in the tubes of the pump, etc., has been shown by experiment not to be an explosive effect of the discharge but is due rather to ordinary diffusion of the gas, the rate of diffusion increasing as the pressure is reduced. The visible diffusion of the afterglow begins after the appearance of the white discharge; its rate then increases as the pressure of the gas diminishes.

Since the white discharge begins at different pressures depending on the electrical intensity acting on the gas, it follows that diffusion at the same gas pressure is rapid or slow according as the afterglow is formed by the white or pink discharge. Hence it is possible that we are dealing with two conditions in the gas, with widely different diffusing rates. It is significant that the glass vessel in which the electrodeless discharge takes place first begins to show strong and enduring phosphorescence at the pressure at which white discharge appears. This shows a sudden increase in the electronic bombardment of the glass after the white discharge begins.

Further experimentation will be necessary in order to determine the nature of the afterglow, and any hypothesis explaining the phenomenon at this time must be based on a rather uncertain foundation. Nevertheless, there are a few facts which give some indication of its cause. It is evident that the afterglow is not due to electronic oscillations started by the discharge and which die down slowly, because Lorentz, in discussing the theory of radiation,[1] cites the interference experiments of Michelson and Lummer and points out that the time required for a vibrating electron to lose half its energy, as shown by its radiation, is exceedingly small. The radiation is reduced to half its original value after forty million vibrations, and since the number of vibrations of yellow light is about 5×10^{14} per second, the time required for the radiation to be reduced to one half its original intensity is approximately 1.0×10^{-7} seconds. The afterglow remains visible for many minutes, there-

[1] Lorentz, Résultats et problèmes de la théorie des électrons. Archives Néelandaises des Sciences Exactes et Naturelles, Series II., Vol. XI. p. 52.

fore its long duration is obviously due to electronic oscillations which are freshly started throughout the time the afterglow continues. Thus the afterglow at any moment must be the total radiation from a great number of separate electronic disturbances, the same being of very short duration, the diminishing number of such new disturbances in each succeeding second determining the rate of decay of the afterglow. If the afterglow is connected with a polymerized state of the gas, as suggested by J. J. Thomson, then the electronic disturbances would correspond to separate reconversions of the unstable chemical compound as the gas gradually returns to its normal state. According to the writer's experiments, the duration of the afterglow depends on the pressure in a marked manner, and since the intensity is also affected, it is probable that the intensity as well as the duration are both connected with the number of collisions that are taking place in the gas. It would appear, therefore, that the reconversions of the chemical compound referred to are started by the collisions of the gas particles. Burke's observation that the afterglow conducts electricity after the ions have been driven out by an applied E.M.F. can be explained on the hypothesis that fresh ionization, accompanying the chemical changes in the gas, takes place all the time the afterglow is present.

I wish to express my indebtedness to Professor E. F. Nichols for suggestions concerning certain parts of this work, and to Dr. Bergen Davis for giving valuable assistance relating to both the theory and the production of the electrodeless discharge.

PHŒNIX PHYSICAL LABORATORIES,
COLUMBIA UNIVERSITY, June, 1906.

THE TEMPERATURE OF SOLID CARBONIC ACID AND ITS MIXTURES WITH ETHER AND ALCOHOL, AT DIFFERENT PRESSURES.

BY JOHN ZELENY AND ANTHONY ZELENY.

1. Solid carbonic acid and more especially a mixture made by the addition of ether or alcohol have long been used for the maintenance of a fixed low temperature. Under reduced pressures the temperature of the substance is reduced still further, and a knowledge of the temperature assumed at any given pressure gives one the means of readily producing and maintaining temperatures between $-77°$ C. and $-115°$ C. We are not aware that any detailed study of the variation of the temperature of the above mixtures with pressure has been made, although du Bois and Wills [1] have obtained the temperature of the carbonic acid snow itself at several pressures.

There are differences of opinion among the different writers as to the effect of adding ether or alcohol to the carbonic acid snow, and the value of the temperature is usually given without any regard to the effect of changes in the barometric pressure. There is disagreement, too, among the values given for the temperature of the carbonic acid snow itself at atmospheric pressure.

Cailletet and Colardeau [2] give $-60°$ C. for the temperature of carbonic acid snow at atmospheric pressure, and $-76°$ C. as the temperature in a good vacuum. For a mixture of carbonic acid and ether at atmospheric pressure they give the value $-77°$ C., and for the temperature of the mixture in a good vacuum they give the value $-103°$ C. For a mixture of carbonic acid and alcohol the value given by them is $-72°$ C.

Regnault [3] gives $-78°.16$ for the boiling point of carbonic acid. Villard and Jarry [4] give the temperature as $-79°$ C. and state that

[1] Beibl. zu d. Annal. der Physik, 24, p. 428.
[2] Jour. de Physique (2), 7, p. 430.
[3] Ann. de Chim. et de Phys. (3), 26, p. 259.
[4] Compt. Rend., 120, p. 1413.

the variations due to the changes of the barometer are insignificant, although at a pressure of 5 mm. they found the temperature of the snow to be — 125° C. They state that at atmospheric pressure no change in the temperature was produced by adding ether to the snow.

Du Bois and Wills[1] give the temperature of carbonic acid snow at atmospheric pressure as — 79°.2 C., with a rate of change of 1° C. for a change of 55 mm. in the pressure.

For the temperature of a mixture of ether and carbonic acid snow Travers[1] ascribes to Olzewski the value of — 78°.2 C. Witkowski[2] gives — 78°.5 C. for the same mixture. Holborn[3] found the temperature of a mixture of absolute alcohol and carbonic acid snow at atmospheric pressure to be — 78°.34 C., with a variation of 0°.20 for a change of 1 cm. in the pressure. Carbonic acid snow itself gave a temperature 0°.10 C. lower.

2. In the experiments here described the carbonic acid snow was obtained from a cylinder of commercial liquid carbonic acid. The temperatures were measured by means of a nickel-iron thermo-electric couple. This was calibrated by the use of six known temperatures. The two temperatures used upon which the values given in this paper mainly depend are: (*a*) the value given above which Holborn obtained with a hydrogen thermometer for the temperature of a mixture of absolute alcohol and carbonic acid snow, and, (*b*) the temperature of boiling ethylene which was taken as — 103°.9 C. for a pressure of 74.0 cm.[4] The measurements were made with a D'Arsonval galvanometer which, with the scale at a distance of 2.6 meters, enabled the temperature to be read to 0°.01 C. The couple was short-circuited after each deflection and the reading taken so as to eliminate the errors due to any thermo-electric forces in other parts of the circuit. Errors due to either a set in the fiber or to hysteresis[5] were eliminated at the same time. The changes in the room temperature were too slight to necessitate any correction for temperature.

[1] Study of Gases, p. 245.
[2] Phil. Mag., (5), 41, p. 301.
[3] Annal. der Physik., 6, p. 245.
[4] Travers, Study of Gases, p. 243. (Wroblewski, Witkowski, Ramsay and Travers.)
[5] A. Zeleny, PHYS. REV., 1906, vol. 23.

3. (*a*) Attention was first directed to the temperature of carbonic acid snow contained in an open vessel. It is known[1] that to maintain a constant temperature the snow must be surrounded by its own vapor. A glass beaker was nearly filled with the snow and the thermo-electric junction was placed in its center.

As long as the windows of the room were closed and the air was well at rest the temperature of the snow in the beaker remained quite constant at its normal value, but the presence of any draughts at once lowered the temperature appreciably. Blowing past the beaker with a bellows and thus rapidly removing the vapor caused the temperature to decrease by over 15° C.

A piece of the snow placed over the junction and held above the table so that the vapor formed could flow downward from the solid had its temperature reduced by over 10° C. below the normal temperature.

A deep vessel only partly filled with the snow and preferably corked so as to leave but a small vent, answers best for maintaining a constant temperature. The snow must however be well packed so as to make a good contact with the junction or else a slightly too high temperature is obtained. On the other hand the stirring caused by the act of packing down the snow seems to increase the rate of evaporation and causes a small temporary diminution of the temperature.

(*b*) In the next place a mixture made of ethyl ether and carbonic acid snow was placed into the glass beaker. The temperature of this remained very constant, unaffected by slight draughts; and the blowing of a strong blast with a bellows by the mixture barely diminished its temperature by 0°.02 C. It seems that the heat received from the air blast almost exactly equalized the cooling due to the more rapid evaporation caused by the removal of the vapor. After the blowing had been continued for some time, however, the uppermost parts of the surface became whitish as if the ether had all evaporated from them and exposed the clear snow. When this point was reached the evaporation was accelerated and the mixture began to cool just as it had done in the case of the dry snow; and by continuing the blowing the temperature of the whole was reduced by several degrees.

[1] Faraday, Phil. Trans., 1845, p. 155. DuBois and Wills, loc. cit.

Under normal conditions however the temperature of the ether mixture is remarkably constant,[1] as long as the snow is moist and as long as there is not enough ether present for a liquid surface to form over the snow.

Stirring the mixture had a tendency to produce a temporary lowering of the temperature by about 0°.02 C. When the mixture is first made a temporary lowering of the temperature by as much as 0°.5 C. was observed. This always disappears soon, however, and may be due to some of the snow dissolving in the ether.

(*c*) A mixture was next made of absolute alcohol and the carbonic acid snow, and placed into the glass beaker. To assume its lowest temperature this mixture must be quite thick, much more so than is necessary with the ether mixture. There should be no appearance of any free liquid throughout the mass of the mixture. Blowing a strong blast of air past the mixture with the bellows caused a rise in temperature of about 0°.2 C. The cooling due to the increased rate of evaporation at the surface is not sufficient in this case to equalize the heat received from the air blast. An increased ebullition in the interior of the mass however prevents the temperature from rising very far. When the blast was continued, the heat from it vaporized so much of the carbonic acid in a short time, that the mass became too moist from an excess of the alcohol, the ebullition became very brisk and the temperature increased quite rapidly.

(*d*) It thus appears that of the three refrigerants, dry carbonic acid snow, a mixture of absolute alcohol and carbonic acid snow, and a mixture of ether and carbonic acid snow, the last is the best one to use for maintaining a uniform temperature. The absolute temperature of the three, however, was found to be identical when they were placed in a deep vessel so as to be surrounded by their own vapor. The differences which were observed for the three at different times for the same barometric pressure did not exceed 0°.02 C.

4. The temperature of the three refrigerants was next measured when they were subjected to different pressures. In some cases

[1] We could not observe any change of temperature when a vessel with the mixture was covered to exclude air, such as is described by Faraday (loc. cit.).

the substance was placed in a long cylindrical Dewar flask 4 cm. in diameter. The opening was closed with a rubber stopper through which the thermo-electric couple passed and from which a rubber tube led to an open mercury manometer and to a water pump. A vessel of large volume was placed in series so as to equalize some of the variations due to the inconstancy of the pump. In other cases the Dewar vessel was replaced by a glass tube of the same diameter. The advantage of this was that it could be placed inside of a large Dewar cylinder to protect it from heat but when the temperature was to be raised the tube could be withdrawn and the process greatly accelerated.

To produce pressures higher than an atmosphere the rubber tube leading from the containing vessel was partly closed by means of a screw clamp. Also in adjusting for the lower pressures the rubber tube leading from the vessel was closed by the proper amount with the screw clamp, while the water pump was operated at a constant pressure. By watching the indications of the manometer and carefully using this screw the variations of the pressure could readily be kept within a millimeter.

The temperature of the refrigerant assumes its final value much more rapidly in going from a higher to a lower temperature than in the reverse direction. In the first case the rapid evaporation quickly cools the mixture to its final temperature while in the second case the heat has to come in through the walls of the vessel. It is especially desirable, therefore, when a Dewar cylinder is used, to approach any temperature from one that is higher. With the protection of the Dewar flask the freezing mixtures evaporate but slowly even at low pressures and so any temperature can be maintained for a long time without a change of material.

5. Eight sets of readings with over a hundred observations were taken with the three refrigerants. The reduced values that were obtained were plotted on a large scale and the points for the three substances all appeared to belong to one and the same curve. It was concluded that the temperatures of the three substances at any one pressure are the same. A single curve was therefore drawn through all of the points obtained. The agreement of the observations was on the whole good although a few of the individual points

varied as much as 0°.5 from the main curve. The observations with the alcohol mixture did not extend below — 100° C.

The values of the temperatures at the different pressures was read off from the curve thus obtained and the results are given in the following table:

The Temperature of Carbonic Acid Snow and Its Mixtures with Ether and Alcohol, at Different Pressures.

Pressure in Centimeters of Mercury.	Temperature. ° C.	Pressure in Centimeters of Mercury.	Temperature. ° C.
2	−116.7	44	−85.2
3	−112.9	46	−84.6
4	−110.0	48	−84.1
5	−107.8	50	−83.6
6	−106.0	52	−83.1
7	−104.5	54	−82.6
8	−103.2	56	−82.2
9	−102.1	58	−81.8
10	−101.1	60	−81.4
12	− 99.4	62	−80.9
14	− 97.9	64	−80.5
16	− 96.5	66	−80.1
18	− 95.3	68	−79.76
20	− 94.2	70	−79.40
22	− 93.2	72	−79.04
24	− 92.2	73	−78.86
26	− 91.3	74	−78.68
28	− 90.5	75	−78.51
30	− 89.7	76	−78.34
32	− 89.0	77	−78.17
34	− 88.3	78	−78.00
36	− 87.7	80	−77.66
38	− 87.0	82	−77.33
40	− 86.4	84	−77.00
42	− 85.8		

It is seen that at atmospheric pressure the temperature of the mixtures changes by 0°.17 C. for a change of 1 cm. in the pressure. This rate increases as the pressure is diminished so that at a pressure of 2 cm. it is over twenty times as large.

The values given by du Bois and Wills (loc. cit.) for the temperature of carbonic acid snow are from 1° to 2° lower than those

determined by us for the snow and its mixtures with ether and alcohol. Thus at 76 cm. pressure their value is — 79°.2 C. and at 4 cm. pressure, — 112° C. The differences appear to be due to the fundamental temperatures assumed for the calibration of the thermo-electric couples.

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June 29, 1906.

MEASUREMENTS OF THE INTERNAL TEMPERATURE GRADIENT IN COMMON MATERIALS.

By Charles B. Thwing.

THAT many metals and common materials are radio-active has been established by the work of several observers. Since the radio-activity of radium compounds produces an elevation of temperature within a mass of the substance, it is to be expected that other radio-active bodies will exhibit the same phenomenon in a much smaller degree.

That the magnitude of the temperature gradient in the common metals and rocks is large enough to be detected and measured seems to be demonstrated by the experiments about to be described.

Apparatus.

The metals were cast in the form of cylinders, 100 mm. in diameter and 25 mm. in height, two such cylinders of each substance being employed. In the case of oxides, etc., in powder form, the substance was contained in paper cartons of the same dimensions as the cylinders, having a circular opening 75 mm. in diameter in one end, which opening was closed by means of a sheet of thin waxed paper.

The thermometer consisted of 116 nickel-iron couples connected to a sensitive D'Arsonval galvanometer. The nickel wires were 0.26 mm. and the iron 0.34 mm. in diameter. The iron wire was tinned and the joints were made by soldering, rosin being used as a flux.

The couples were wound radially on a ring of mica, the inner diameter of which was 25 mm., the outer 125 mm., and were insulated and protected from moisture by a coating of wax composed of bees-wax and rosin. The entire series of couples has a resistance of 15 ohms.

The galvanometer for this work was furnished by Leeds and

Northrup. The suspensions were of silver, the resistance of the galvanometer being 25 ohms. A deflection of 1 mm. at 1 m. distance corresponds to a temperature difference in the couples of 0.0000055° C. The image of the scale was clear and the needle at rest, so that tenths of a scale division could easily be estimated.

In order that small differences of temperature might be measured it was of course necessary that the specimens and thermometer be protected from external temperature changes. This condition was quite perfectly met by placing them in an ice-calorimeter, as indicated in the figure. The inner cylinder of the calorimeter was 175

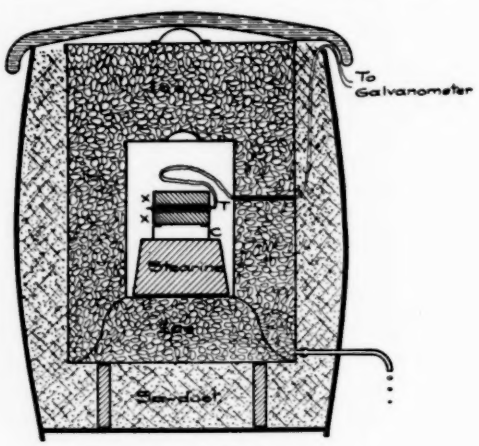

Fig. 1.

mm. in diameter and 250 mm. high; the outer cylinder was 400 mm. in diameter and 720 mm. high. The whole was contained in a barrel 830 mm. high and packed with sawdust. Heavy woolen blankets covered the top. A tube between the cylinders allowed the galvanometer leads to enter, and the outer cylinder was provided with a rubber drain-pipe near the bottom.

Ice was supplied on alternate days and was crowded down to the bottom of the calorimeter twice daily, about 5 kg. per day being the amount consumed. The ice was of uniform texture (artificial ice) and was said to be made from distilled water.

The galvanometer leads were of flexible copper wire, with rubber and cotton insulation, the portion entering the calorimeter being further coated with wax.

The pair of specimens, X, X, to be examined rested with the thermometer, T, between them upon a paper carton, C, similar to those used for studying powdered materials. The carton, in turn, rested upon a block of stearine which lay in the bottom of the calorimeter.

The time required for a specimen, after being placed in the calorimeter, to reach a steady temperature was from twelve to twenty hours, depending mainly on its conductivity for heat. After this interval had elapsed the deflection remained nearly constant for an indefinite period. The longest period tried was fifteen days. As a rule three or four days seemed sufficient for making a determination.

Results.

Of the substances thus far examined, all, without exception, show an internal temperature gradient. It is intended to extend considerably the list of substances included in the table. The results obtained seemed of sufficient interest, however, to justify their publication at the present time.

Table I.

	Deflection.	t	t cm.
Lead	5.4	0.000059	0.000020
Antimony	3.9	0.000043	0.000014
Zinc	3.1	0.000034	0.000011
Iron	2.9	0.000032	0.000011
Copper	2.8	0.000031	0.000010
Aluminium	4.1	0.000045	0.000015
Aluminium oxide	28.0	0.000308	0.000103
Magnesium oxide	16.1	0.000176	0.000059
Marble	1.4	0.000015	0.000005
Sandstone	7.2	0.000079	0.000026

The second column gives the definition in mm. with the scale 50 cm. distant. The third column gives the temperature 3 cm. within the specimen when the surface and surroundings are at 0°. The fourth column gives the gradient in degrees per centimeter.

Sources of Error.

The most obvious sources of error are (1) thermo-electromotive-forces in the galvanometer itself or in the leads; (2) chemical elec-

tromotive forces due to moisture in the insulation of the elements; (3) variations in the temperature of the calorimeter.

Concerning (1) it was found that during rapid changes of temperature of the room a deflection was observed if the galvanometer was short-circuited through the lead wires. This deflection depended upon the direction of change of room temperature and was divided by 2 if a resistance equal to that of the galvanometer was added to the circuit. Under ordinary conditions this error was not above 1 or 2 per cent. of the observed deflection. Cooling the joined ends of the lead wires 15° or heating them a like amount produced no deflection.

Concerning (2) it is to be observed that the order of nickel and iron in the thermo-electric series is opposite to their order in the contact series, so that any leakage between the elements would produce a deflection opposite in sign to the deflection observed. A leak between the last iron element and the copper lead wire might produce a deflection in the same direction as the one observed.

Concerning both (1) and (2) it remains to be said that any currents due to the sources mentioned should not be dependent upon the presence of the specimens surrounding the thermometer but should be equally in evidence when no specimens are present. It is found, moreover, that when the thermometer is exposed alone in the calorimeter, resting upon the rim of the paper carton, no deflection save a small one of variable sign is observed.

In regard to (3) it was found that the temperature of the calorimeter was raised by about 0.00001° to 0.00002° by the melting of the ice away from the bottom of the inner cylinder during the 12-hour intervals between the times of packing down the ice. This was shown by a rather rapid increase of the deflection immediately following the packing followed by a slow return to the first reading.

In brief, there seems to be no source of error present when the specimens are in place which is not equally present when they are removed. When the specimens are removed deflections as large as 1.0 are observed. With the specimens in place deflections corresponding to a negative gradient are never observed, and the variations observed never exceed 20 per cent. of the total deflection. It seems certain, therefore, that the values given in the table represent

the gradient under the conditions described to within from 10 to 20 per cent.

Concluding Remarks.

The obvious explanation of the observed phenomenon is, of course, to assume that the temperature is due to radio-activity, either of the substance itself, or of radio-active substances contained as impurities. It seemed not out of the range of possibility that oxidation of the surfaces of the specimens might generate a measurable amount of heat. It was found, however, that boiling the iron cylinders in purified vaseline and testing them with a film of the vaseline still on them showed no variation in the results. The vaseline used is remarkably free from either acid or alkali and does not corrode metals immersed in it for many months.

Substances, moreover, like MgO or Al_2O_3 can hardly be thought of as undergoing any chemical change during the experiment.

The order of magnitude of the temperature gradient in different substances does not, of course, indicate the order of their radio-activity, since the heat generated is conducted away more rapidly in good conductors like copper and aluminium than in the more poorly conducting metals and oxides.

The magnitude of the temperature gradient found is more than sufficient to account for the known temperature gradient below the surface of the earth on the assumption made by Rutherord in his criticism of Strutt's results that the entire mass of the earth is radio-active to the same extent as the portions found near the earth's surface. Since, however, the values for the radio-activity of substances at the surface of the earth found by different observers using widely different methods all agree in being too large to be explained on this assumption, it may be worth while to consider another hypothesis, *viz.*: that the radio-active materials are to be found mainly in the earth's crust.

On the hypothesis that the elements have evolved somewhat in the order of their atomic weights under conditions of increasing agglomeration of the particles composing the gravitating mass, it might appear that the chief condition for stability of the complex atoms was enormous pressure, a condition better fulfilled far below the earth's surface than at the surface. Elements, therefore, which

at a later period found themselves nearer the surface of the earth than at the period of their birth might be expected to show radioactivity.

The body of observed facts is as yet far too meagre to justify anything more than the merest speculation upon this most fascinating subject. It would seem, however, that henceforth the geologists may be permitted to claim such periods for the life of the earth as their various theories demand without fear of contradiction from physicists.

It is the writer's intention to extend the list of substances examined and to check the observations by control experiments, some of which are now in progress.

I desire to express my thanks to the American Academy of Arts and Sciences for appropriations from the Rumford Fund covering the expenses of the investigation, and also to the President and Director of the Physical Laboratory of Adelbert College, who have placed at my disposal a very suitable room and all available facilities for carrying on the work.

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